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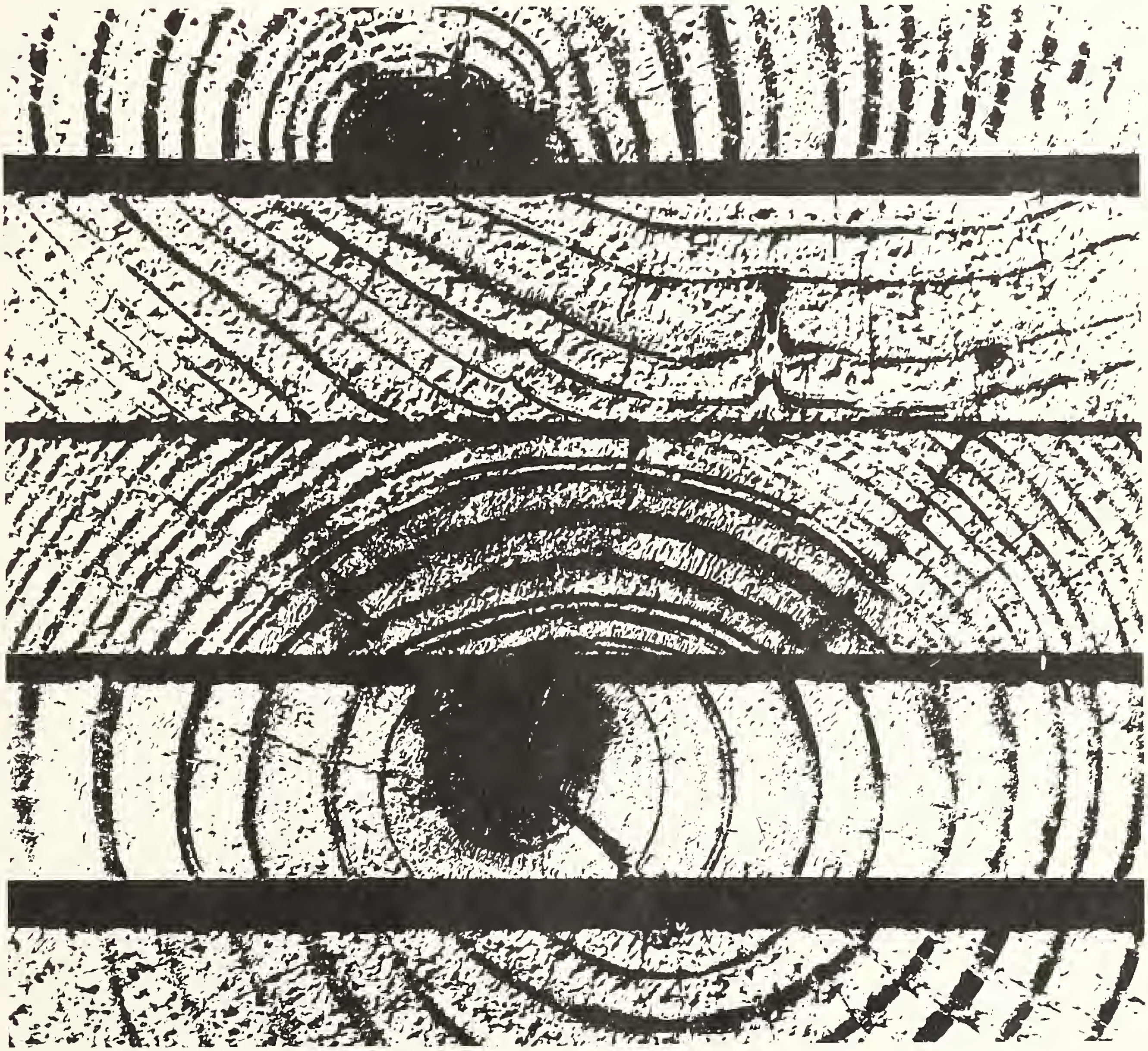
How the Environment Affects Lumber Design: Assessments and Recommendations



How the Environment Affects Lumber Design:

Assessments and Recommendations

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PREFACE

Safe but efficient structural utilization of wood depends on both a reliable assessment of basic strength properties and an understanding of long-term, in-service response of wood to its processing and use environments. In 1978, the Society of Wood Science and Technology in cooperation with the Western Canadian Forest Products Laboratory sponsored a symposium on the structural use of wood in adverse environments. That symposium focused attention on the importance of both the processing and use environments through state-of-knowledge summaries and reports on current research.

The need for additional information on how lumber properties are affected by the process and use environment led to this workshop. Scientists and Engineers from throughout North America, Europe, and Japan were invited to participate in the workshop. Twenty-two persons representing a variety of disciplines then met for 2-1/2 days to discuss research needs, strategies, and priorities for improving the data base of knowledge of how lumber, taking size and grade into consideration, responds to its environment. Several others who were unable to attend submitted papers for discussion at the workshop.

Participants submitted papers discussing past and current research and identifying future research needs. On the second day of the meeting, participants were divided into three task groups for concentrated discussion within the loosely defined topic areas of biological and chemical factors, temperature and moisture factors, and load history factors. At the final session, each group presented a consensus statement; this was followed by a presentation summarizing the main research needs and common areas of concern as expressed in the three groups. The workshop concluded with a discussion of strategies for research implementation.

The assistance of Margery Dean, Lisa Marin, Dobbin McNatt, and Jerrold Winandy of the Forest Products Laboratory contributed to the success of the meeting and is gratefully appreciated.

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TABLE OF CONTENTS

COMMENTS ON RESEARCH NEEDS: SUMMARY DISCUSSION

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INTRODUCTION

Significant deficiencies in knowledge of the effect of environment on the design properties of lumber, timbers, and poles and piling have been identified by the workshop participants. Discussion groups were established to cover three areas: biological and chemical factors; temperature and moisture factors; and load-history factors. Each group produced a document outlining the research needs, methods for solution of the problems, and comments on implementation of the research results for design.

In reviewing the summaries prepared by individual groups, incorporating elements of the group discussion, several major areas of emphasis for future research have been identified that are common to the groups. Within each group, a need was emphasized to develop a fundamental data base on the behavior of lumber, timbers, and poles and piling. In some cases, this data base could not be developed unless the interaction of the wood with non-wood factors, such as metals, chemicals, and fasteners, was considered. Accordingly, this brief summary discussion will contain references to these additional aspects which, in many cases, will play a dominant role in the design of future experiments undertaken to provide the data base on lumber performance.

In developing the recommendations for future research, emphasis was put on trying to identify the needs, current and future, for all user groups. This vital, but extremely difficult, task is a necessary part of any planning exercise. However, it can only be considered incomplete since it is impossible to define all future needs. The effort is useful, however, since one is forced to give careful consideration to the range of parameters and the potential impact of interaction of fundamental variables identified. Perhaps the most severe criticism expressed about the current data base for lumber relates to the lack of adequate information about the effect of interactions of variables such as temperature, moisture content, loading conditions, time and decay hazard, to permit the satisfactory prediction on the performance of lumber in structures. Accordingly, there has been an effort to identify the research areas where study of the interaction effects is most important. There also is the recognition that future research must carefully consider the relevance of interaction effects, thus to ensure that any new data base developed will have the information required for assessment of interaction effects encountered in service.

RESEARCH NEEDS

Needs identified can be discussed under five topic areas. The topic areas will be presented and some of the most important issues raised in the discussion groups will be brought together.

1. Strength and Stiffness of Lumber, Timbers and Piles

Several recent studies have reemphasized the fact that the influence of parameters, such as temperature and moisture content, interacts with material quality level as expressed by parameters such as strength ratio. In the studies of effects of temperature and moisture content, special emphasis should be placed on establishing the ranges of these variables for which effects on strength properties are immediate and reversible, and the ranges for which permanent effects occur as a function of material quality. Effects of environment also interact with loading conditions. Extensive work is required to provide the data base necessary for predicting the long-term strength and deformation behavior of lumber for in-service conditions in which environment and loads are time varying. Experimental difficulties will generally limit consideration of these interaction effects to some conditions manageable from the testing viewpoint, such as constant and ramp loading coupled with constant and cyclic environments. However, it is most important that the researcher must not lose sight of the fact that

engineers and architects must design for actual service conditions, which can be significantly different than the experimental conditions and, therefore, we must also develop the analytical tools required for predicting behavior for service conditions that are not tested.

The biological group emphasized the importance of improved information on the effects of chemicals and the chemical environment on wood mechanical properties. Particular attention should be given to the effects of steaming treatments that occur in treating operations.

Duration-of-load research must be undertaken to determine the effects of load conditions on the strength and stiffness of lumber for all structurally important modes of fracture. Experimental studies for loading conditions, such as constant load and ramp load, must be coupled with analytical techniques for establishing the effects of actual loading conditions on the long-term behavior of lumber. Long-term loading studies must also consider the effects of interactions of loading conditions with environmental cycling, treating conditions and chemical environment to develop an adequate data base for refining the current design codes. Establishing the effects of loading conditions on the time-to-failure for lumber is the crucial issue to be resolved, if new reliability-based design procedures are to be implemented for wood structures.

In developing the data base for lumber, it is necessary to keep in mind that the resource base is not stable. Increased use of smaller diameter logs and lower density material, having properties considerably different from lumber currently utilized, must be anticipated. Use of presently under-utilized softwood and hardwood species, diseased and insect infected timber, burned and other types of damaged timber also is increasing.

2. Nondestructive Testing

Nondestructive predictors of strength and stiffness properties have been utilized in a variety of research and industrial applications for many years. While the techniques currently available have worked well, this area of research activity has been emphasized, since many benefits can be derived by further refinement of the prediction models and instrumentation systems. For example, all the material-property research suggested in the previous section would be significantly simplified if the strength of individual members or the strength distribution of a group of members could be predicted more accurately. With these improved tools, groups of specimens with similar properties could be selected to assess the effects of various "treatments" compared with the properties of control specimens.

In addition to developing techniques for predicting the strength of "virgin" material, there is an acute need for reliable residual-strength assessment procedures. These would find application in a wide variety of situations, but they are of particular interest in assessing the residual strength of elements subjected to biological degrade, fire, and chemical attack.

3. Hazard Identification

Several types of "hazards" have been identified that must be quantified if the utilization of lumber is to be improved and rationalized. Perhaps the most obvious is the decay hazard. Further research is required to map regional hazard levels, thus permitting the designer to provide adequate structural detailing to ensure structural integrity for the design lifetime of the structure. This activity must be accompanied with potentially a much larger program oriented to identifying and quantifying the influence of microclimatic factors within the structural envelope. Research needs in this area are emphasized by the emergence of many problems of new insulation requirements brought about by energy considerations.

Loads are a second type of "hazard" to be considered. Load research is often accepted as being out of the terms of reference of wood specialists. Load-data requirements were considered to be similar for all structural materials and appropriate for all materials. Accordingly, the development of load information has been left to load committees often unfamiliar with the special behavior characteristics of wood. Wood specialists must become more actively involved in the development of load codes. In particular, we must ensure that the load committees provide the type of basic load models required for predicting the behavior of timber structures. Duration-of-load effects in wood are load-history dependent, thus we must have an adequate characterization of the load history for loading conditions, such as snow, wind, earthquake, occupancy loads and load combinations, to permit refined assessment of the effect of load history on time-to-failure for wood members and systems. At the present time, we do not have adequate load-history information. Unless we bring attention to our needs, we

will not have this information to couple with the refined mechanical-property data base that is the subject of this workshop.

4. Fasteners

If lumber is used in a structural system, forces must be transferred from one member to another. This load transfer is usually accomplished with some type of mechanical fastener. There are many unresolved problems related to the performance of fasteners in timber that cannot be neglected in developing the data base on lumber performance. In particular, we are concerned about the short- and long-term effects of chemicals used in treating processes and the chemical constituents in wood, particularly under high moisture conditions, on the performance of the wood-fastener system. In this case, we have considered the effect of the fastener in wood to be essentially inseparable from the consideration of the wood behavior alone because of the need to join elements into systems. If the interaction of the wood with the fastener is not considered, then once again we will not have an adequate data base for refining design criteria.

5. Maintenance Requirements

A general concern has been raised about the lack of adequate guidance available to designers, engineers, building owners and inspectors on maintenance requirements for wood structures. Minimum maintenance requirements to ensure structural integrity are needed to establish regular maintenance programs in occupied and vacant structures.

PLANNING AND PRIORITIES

Identifying research needs on the effects of environment on the mechanical properties of lumber is relatively simple. The challenge for the researcher is to quantify the ranges of variables that must be considered, identify the important interactions and design rational experiments to establish the behavior of the materials considered. The information developed should be of a type that can be incorporated into a compatible data base on material behavior, so that the information will be useful for solving a wide variety of problems, many of which cannot be foreseen at this time. We must keep in mind the need to model the behavior of real environments and loading conditions for real materials expected to perform atisfactorily for service lives of 50 years r more.

Design codes for all structural materials are being transformed to reliability-based formats. For timber codes this activity has proceeded more quickly in Canada than in the United States. Experience suggests that the new data base proposed for lumber behavior will be used extensively in developing the new design criteria for limit states and other probabilistically-based codes. Since these new approaches emphasize the need for a knowledge of the distributions of properties, it is mandatory that studies be undertaken to investigate behavior for the complete range of properties expected in the product. This is particularly important for wood structures which are dominantly redundant-member systems in which we rely on load-sharing actions to produce the high degree of structural reliability inherent in wood structures. We are now entering a period in which we can no longer accept the fact that we cannot quantify the structural adequacy of wood structures. As the competition for resources increases, we have a responsibility to provide rational analysis techniques and data suitable for the designer of timber structures to effectively utilize the one renewable structural material nature has provided.

Research priorities are extremely difficult to establish for others, since so many acceptable approaches can be used to establish selection criteria. Having identified a wide variety of needs, perhaps all we can suggest is that there should be a balance between short-term and long-term projects. Many of the studies inherently involve long-term commitments of staff and facilities that are not within the capability of all research organizations. Thus, perhaps one of the most important contributions of meetings of this type will be a commitment by the interested parties to try to achieve a high degree of cooperation, in an attempt to ensure that a proper balance is achieved between the short-term and long-term research needs. Lacking this balance, we will not achieve the objective of providing the new data base required for rationalizing the performance of lumber, timbers, poles and piling so urgently required.

RESEARCH IMPLEMENTATION[1]

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INTRODUCTION

We who do research have to realize that the products of our work are of no value until somebody uses them. Only then is our service completed for the society that pays our salaries and provides our facilities. Implementation is, therefore, a most important aspect of our research and it behooves us to keep watch over ongoing applications in the everyday world so that we can plan and steer our work in order that it can be most effective when implemented.

In my field of wood structural engineering I have come to recognize two separate activities with which the researcher must eventually interface. One I call the paper game and the other the real game. The labels are not necessarily meant to be facetious and each activity is as important as the other. The paper game relates to plans, specifications, engineering calculations, codes, etc. and these days of increased liability awareness require that the game be played meticulously. The real game relates to the actual structure that is created and the basic intent is that this activity follow the rules and principles of the paper game. Unfortunately, in light-frame construction this is sometimes not the case and the two games seem somewhat irrelevant to each other. This is probably due to the lower cost of such buildings which does not ordinarily allow for payment for inspection services. The main motivation for adherence to specifications on the part of the builders and suppliers is fear of liability exposure. Some builders and some suppliers seem to ignore the liability risks either by choice or lack of awareness. The trend, however, is now toward realization and acceptance of responsibility because of general social trends creating more new laws to protect the consumer.

An example of discrepancy between the paper game and the real game can frequently be found in roof trusses for houses. Most truss fabricators build carefully according to plans and specifications using the required grades and species of lumber. It is possible, however, to find trusses going into houses built with lumber that cannot calculate to carry the design loads, and with poorly made connections that obviously could not pass an actual load test. But these roofs do not fall in. The reason is that, once the house is finished, residential trusses get so much mechanical assistance from the plate action of the sheathing and support from interior partitions that they do not actually need the strength required by the paper game. Clear span, widely spaced trusses for a farm or commercial building can, on the other hand, seriously need agreement between real and paper requirements and they must be both engineered and built correctly. The reason for such variable relationships between the real and paper games are not due to neglect or oversight but arise because we lack sufficient knowledge to correct them in a safe and consistent fashion. For instance, we might, at great expense, be able to solve for most of the unknowns in a laboratory-built house roof but we do not know the extent of variation in field practice that would have to be available if implementable new design rules were written.

Much of our research feeds into the paper game arriving there via the ASTM, The National Design Specification, and like documentation emanating from product line associations and code writing agencies. The researcher should be aware of how the subject of his ambitions is handled in the documents now, if at all, and should develop some vision as to how he can eventually feed the proposed results into them. Just writing good, technically sound scientific journal articles is not likely to be enough to trigger implementation because such articles do not always communicate that well to the people who are closer to and more active in implementation. Also, it can happen that the laboratory experiments that yield the quantitative

[1]Paper presented at the Workshop of Research Needs on Effect of the Environment on Design Properties of Lumber, Forest Products Laboratory, Madison, Wisconsin, May 28-30, 1980.

conclusions are performed with irrelevant species and samples. If the research program were keyed to implementation awareness at the outset, such would not be the case.

Another good route to implementation lies in the development of research results that clearly represent a profit potential for private enterprise. If costs can be cut, financial risks reduced, or a profit can be made by utilizing new research results, the researcher need have little concern about the incidence of implementation if he has done a fair job of communicating his results.

Lack of contact between people immersed in the paper game and those in the real game can cause serious misinterpretations. The heavy snows of recent winters caused numerous roof failures, many of these roofs were framed with wood. The first reaction of those who confine themselves mostly within the paper game has been to recommend increases in design loads. My experiences with those closer to the real game indicate that the actual problem could lie elsewhere. Most roof failures in light-frame buildings, that I have heard reported from reliable sources over 25 years, stem from mistakes or omissions in the construction process. The types of builders prone to these errors will be relatively unaffected by design load increases in the engineering calculations--construction faults will continue unabated. If design load increases are made in such a case, fabricators will be overbuilding with commensurate cost increases but consumer safety will not be much affected. The moral of this story is that the beginning point of research on a topic of this sort is to first define the real problem. Then, on completion of the study, implementation can affect improvement rather than add confusion to the problem.

Some years ago we tackled a problem called "nail-popping" which is the development of unsightly defects in drywall construction due to latent emergence of the originally hidden nails. We identified moisture changes in the wood as the cause and performed extensive research leading to our prescription of a solution. It happened that there was much industrial interest in our early publications on this work and we were privileged to then work with many field people as they tried our theories. This led to the discovery that our laboratory solution did seem to work but in only about half of the field cases. More thorough field studies led to the conclusion that errors made in wallboard application and nailing were equally likely to cause the same defect independent of moisture control. When both solutions were put together, the problem was finally controlled. We learned the somewhat embarrassing lesson that the beginning point of research should have been to find out the real scope of the problem.

Since the applied research scientist frequently finds it difficult to assure himself that he is correctly diagnosing and addressing his problems and also frequently has no real knowledge about how eventual implementation can take place, it is best to carefully consider guidance recruited from the areas to be touched by the research. A committee of consumers, industrialists, researchers from contiguous areas, etc. can help define the problem, help keep the research on target and can assist greatly in implementation. As a participant in the truss lumber research program developed by the U.S. Forest Products Laboratory and the North Central Experiment Station, I can attest to the positive benefits resulting from an advisory committee made up of a truss manufacturer, a truss plate manufacturer who also provides engineering, a lumber sales executive, and a university lumber research worker. This group brought perspective to the planning and continuing guidance as to the usefulness of results. Research in progress always requires revision of plans and changes in the intensity of its various efforts. The advisory committee gave us repeated assistance in this very important function and greatly improved the program. A side benefit of this type of interface is that the user group (industry in this case) is kept aware of the research and anticipating the results. Implementation can then be more of an automatic flow process rather than requiring a long drawn-out "sales" procedure once the research is completed.

Once the problem has been accurately defined, I most frequently favor a research plan that attempts to create or relate to an analytic model of the phenomenon under study. This, of course, includes stochastic modeling where needed to deal with the uncertainties of variability. The objective of science is to project the detailed and specific data obtained within the environment of experiments beyond the laboratory into as wide a variety of real world situations as possible. The analytic model or system is the vehicle of mathematically described sciences for doing this. The very complete and comprehensive material behavior model presented here by R. C. Tang serves as an example of the broad blueprint needed to cope with the many variables involved. It will take all of the science power assembled within this group to quantify Tang's symbols with each project being a justifiable research project of its own. The great feature of each individual study is,

however, the fact that the total assembly can represent powerful progress far beyond the most hoped-for capabilities of any one individual or organization.

The implementation of analytic systems from the laboratory must be undertaken with a severely critical posture to be sure that real problems are actually solved. Trial implementation sometimes shows that the research task is really not complete and we must "go back to the drawing board" to melt in the new information and have another try at the research. It is only by such trials and recycling that analytic models can emerge as useful practical tools. This latter aspect is of particular importance in structural wood systems because implementation relates to life safety and the consequent involvement of building codes. New analytic systems must be accompanied with the assurance that they yield safe and accurate answers at a point far beyond the reach of laboratories.

While it has been previously mentioned, it is worth repeating concentration on the fact that some research topics relate to such critical problems in the real game that implementation can be almost automatic. These are often difficult problems not easily fitted into the patterns of scientific methodology, but they badly need solution and progress of any kind will be welcomed by the user community. A few of these topics are worthy of specific mention here.

Growing trends in product liability coupled with increasing sophistication in building products and systems bring many important research problems before this group. Quality assurance through inspection of inplace systems is a way to meet these needs but new or better tools are required. Field techniques for checking the quality of wood treatments are needed along with equally simple methods for checking moisture content in salt treated wood products.

Thermal-moisture problems abound in wood frame construction now that we face energy shortages because the first reaction has been a head-long increase in the amount of insulation. The light-frame building is actually an evolutionary product that has been balanced as a symphonic product meeting a simultaneous array of requirements. The building provides strength, fire safety, durability, moisture control, thermal protection as well as vibrational and acoustic satisfaction--all within the framework of economic feasibility. If one and only one of these variables is greatly changed without due regard to interaction with the others, trouble can result. Those of us in a position to observe field practices fear that much potential waste is being created by increasing insulation without due regard to vapor movement, needs for ventilation and the possible effects of increased accumulations of moisture. We have tools for measuring equilibrium moisture content but we need better ones particularly for temperatures below freezing. We need to develop quantitative tools for appraising vapor barriers which are never completely effective. We need similar methods for defining ventilation needs in tight spaces such as wall cavities so that moisture accumulation can be controlled at a given level. We need to know the levels of moisture accumulation that reduce the effect of insulation and how great this effect may be. We need rules for guarding against mold growth that could be injurious to health in tight frame houses as well as damaging to the wood structure itself.

Small logs are now more heavily used along with new and efficient machinery for their processing. Lumber packages can now be commonly found with many pith related pieces. This means that more juvenile wood is being used and there also may be an increase in the amount of compression wood going into framing. In the real game we have almost no means for even quantifying the amount of such materials let alone predicting their degree of influence on strength and other important properties. The recent prevalence of separations between ceilings and wall partitions in a winter cycle in homes and similar buildings has become a serious problem. Its exact cause or causes are, as yet, unknown but the problem appears to be stochastic in nature. Ceiling-partition separation, CPS, has been observed in a wide variety of circumstances and none of the "off-the-shelf" answers usually satisfactory for building problems will suffice in this case. The investigative thrust now is to find the influences of materials and systems of material combinations on the probable occurrence of CPS. Increases in juvenile wood and compression wood in the market may relate to the problem and we must develop both more basic and applied knowledge about these lumber characteristics.

In the last two to three decades light-frame construction has moved out of the category of stick building and into component construction. Components such as I beams and trusses are complex from an engineering standpoint but greatly increase the efficiency of the wood resource by doing a better job with material reductions in the order of one-half. Their use, however, brings forth many longstanding problems but with new importance. Load-duration effects for structural wood materials and their connections are simply

treated in current engineering practice and serious questions have been raised as to their adequacy. Heavy research commitments are being discussed in this area now, but I fear that connections may be neglected and it is the connection that makes the component what it is. Eventually to follow will be questions on the influence of partial decay on the integrity of such structures. Buildings are bound to leak and one can almost guarantee that flat roofs will leak. Water leaks foster decay. Subsequent structural repairs are expensive and means are needed for detecting early symptoms of decay and appraising the associated loss of strength. These component related areas of concern provide a wealth of topics for wood researchers that will, in turn, yield an almost open avenue of implementation if progressive results can be realized.

The floor is a singular and unique portion of the building in that it is the only surface involving constant human contact. As a result, the parameters of human satisfaction with floors are much more numerous and complex than those for walls or ceilings. Current engineering treatment of wood floor framing is very simple and evolutionary being based mainly on experience with traditional joist support systems. Problems relating to dynamic effects have turned up in connection with more modern floor framing systems. The main effects concerned are vibration and impact transfer which are largely neglected in contemporary engineering practice for lack of fundamental knowledge. The dynamics of connected wood systems represents a fertile field of problems that have strong implementation pull if they can be solved.

As a final word, I would like to point out that a product of science intended for use in wood construction has exponentially increased implementation chances if the final tool can be made simple to use and correspondingly simple to check calibrate. Factory and field environments are generally hostile to the requirements of complicated high technology methods requiring highly educated operators. The devices used can be as complex on the inside as necessary including enclosed computers but their operation must be quick and simple. Methods employing simple devices but complex in theory must also be refined to concise instructions and error-resistant charts, graphs, tables, etc. Field complications can reassign research back into the archives where it must await future innovations. The payoff intended by the original creator may then be delayed many years beyond his envisioned time of implementation.

EFFECT OF ENVIRONMENT ON LUMBER PROPERTIES--[1]

A PERSPECTIVE FROM APPLICATION

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ABSTRACT

Judgments about the impact of the use environment on lumber properties are essential to efficient lumber use. Product associations, code groups, practicing engineers, and consensus groups such as ASTM use the existing data base on environmental influence to make judgments and recommendations. Setting priorities for improving this data base is the objective of this workshop. The needs of the user community should be considered as this task is carried out.

INTRODUCTION

It is a pleasure to open this workshop with people present from so many different disciplines. Co-sponsorship of the workshop by the Society of Wood Science and Technology testifies to the intent to touch all skills that interact in the field of wood science and technology. Our own goals, as the other sponsor, include furthering the emphasis on interdisciplinary study that was initiated by SWST in the 1978 Symposium on the Use of Wood in an Adverse Environment. The scope of the workshop is truly multi-disciplinary and international.

The nature of our task implies both cooperation and communication. Individuals preparing for the workshop have expressed the concern that they may have reached a point beyond which their experience could not take them, yet their goal had not been achieved--the influence of the environment on the properties was not fully explained. In essence they were saying "Others are needed to share the burden of this problem, to apply other knowledge and to interpret results." We must be prepared to share the conclusions of this workshop so we communicate our concerns and our suggested priorities for action. Without cooperation and communication this multidisciplinary effort will not bear fruit.

[1]Paper presented at the Workshop of Research Needs on Effect of the Environment on Design Properties of Lumber, Forest Products Laboratory, Madison, Wisconsin, May 28-30, 1980.

TARGET

Why is a multi-discipline, international format appropriate for our workshop? Because our evasive target, the effect of the environment on the performance of structural wood products, touches all of our research and implementation activities. In fact, there are so many facets to this subject that we need to define carefully the technical scope of this workshop. For example, applied research in this area stands on the shoulders of fundamental research. And research results must be translated into action through implementation channels. Yet our major thrust should be to develop a relevant data base on the environmental influence on lumber so that responsible judgments can be tailored to individual needs. This data base, I believe, is our specific technical target at this workshop.

BACKGROUND

Our task in the workshop is to define our environmental problem areas with research priorities. As a preface to this, my task is to provide a reference base from a perspective of subsequent application. I will briefly review how our data base as scientists is interpreted and applied by various users. I hope this touch of relevance will provide insights to our subsequent discussions.

Decision Making

The world of application has a feature which sometimes escapes the bench scientist--decisions are mandatory. As researchers, it sometimes is too easy to defer a decision until later--"when more information is available." Not so in the engineering world. An uncertainty is either accounted for in some manner or the product or process is discarded in favor of an alternative. Thus, the environmental concerns that relate to wood are currently considered in all phases of design and application. We are here because we believe the information base available for this consideration is inadequate and because we would like to provide for better interpretation through more adequate data.

Engineering Judgment

The process of "engineering judgment" that our data base serves may be placed in four general categories: (1) standardization, (2) design and product specification, (3) regulatory, and (4) engineering practice. I would like to provide some specific examples of the manner in which these different categories of implementors use "our data base."

Standardization

This is typified by consensus bodies such as the American Society for Testing and Materials (ASTM) and the American National Standards Institute (ANSI). A balance of consumers, producers, and general interest members is a keystone in these organizations. The subject matter committees, in concert with our data, standardize a product or a procedure. Efforts are made to simplify to ease application. Examples of adjustments made to lumber that may be of concern to us include (a) moisture content, and (b) duration of load.

Moisture Content.--ASTM Standard D245 applied adjustments for different moisture conditions to six mechanical properties of lumber (ASTM 1979). Based on data available to the committee these adjustments, when accepted, were standardized to be independent of species and grade. Other properties of interest in design are not covered by this standardization process.

Duration of Load.--In a manner similar to that of moisture content, the ASTM Committee has adopted the so-called "FPL load duration curve" (ASTM 1979, Gerhards 1977). This is the worldwide reference for duration of load adjustments for lumber. It recognizes no sensitivity to grade, size, or moisture content.

Design and Product Specification

Examples of organizations specializing in specifications for wood products include the American Wood-Preservers' Association, and the National Forest Products Association. Each attempts to quantify for the product user those design features which, in their judgment, are the most critical and tractable. For this, they use the data base on environmental influence. To illustrate the need for data, excerpts from the National Design Specification will be used for illustration (NFPA 1977).

a. Treated Wood.--The National Design Specification recognizes the existing data and current practice in these excerpts:

> 2.2.3–Preservative Treatment
>
> The design values provided herein apply to wood products pressure-impregnated by an approved process and preservative (see Reference 37, Appendix I), except as provided in 2.2.5.4.
>
> 2.2.4–Fire-Retardant Treated Wood
>
> 2.2.4.1 For lumber pressure-impregnated with fire-retardant chemicals, the design values otherwise permitted herein shall be reduced 10 percent. (See Reference 37, Appendix I.)
>
> 2.2.4.2 The design values for structural glued laminated timber pressure-impregnated with fire-retardant chemicals before or after gluing are dependent upon the species and treatment combinations involved. The effect on strength must be determined for each treatment. The manufacturer of the treatment should be contacted for specific information on fire-retardant adjustments for all recommended design values. The resulting values are subject to duration of load adjustments as set forth in 2.2.5.
>
> 2.2.4.3 The design values otherwise permitted herein for loads on fastenings shall apply to fastenings installed in wood products pressure-impregnated with fire-retardant chemicals, provided such values are reduced by 10 percent and further provided the wood is dried after treatment in accordance with the American Wood Preservers Association Standard C20, Structural Lumber:Fire-Retardant Treatment by Pressure Processes, or Standard C27, Plywood:Fire-Retardant Treatment by Pressure Processes, as applicable. (See Reference 37, Appendix I)
>
> 2.2.5.4 For members pressure-impregnated with preservative salts to the heavy retentions required for "marine" exposure (see Reference 37, Appendix I), the impact load duration factor in 2.2.5.3 shall not apply.

b. Moisture Content and Temperature.--The National Design Specification considers carefully temperature and moisture content, as well as the interaction between the two variables. The presentation cannot quantify the time aspects of permanent effects, however, which suggests limitations in the data base when viewed as a source of recommended practice for full size products. This portion on temperature effects comes from Appendix C:

> C.1. As wood is cooled below normal temperatures, its strength increases. When heated, its strength decreases. This temperature effect is immediate and its magnitude varies depending on the moisture content of the wood. Up to 150°F, the immediate effect is reversible. The member will recover essentially all its strength when the temperature is reduced to normal. Prolonged heating to temperatures above 150°F can cause a permanent loss of strength.
>
> C.2. In some regions, structural members are periodically exposed to fairly elevated temperatures. However, the normal accompanying relative humidity generally is very low and, as a result, wood moisture contents also are low. The immediate effect of the periodic exposure to the elevated temperature is less pronounced because of this dryness. Also, independently of temperature changes, wood strength properties generally increase with a decrease in moisture content. In recognition of these offsetting factors, it is traditional practice to use the design values from this Specification for ordinary temperature fluctuations and occasional short-term heating to temperatures up to 150°F.
>
> C.3. When wood structural members are cooled to very low temperatures at high moisture contents, or heated to temperatures up to 150°F for extended periods of time, adjustment of the design values in this Specification may be necessary. The approximate average factors given in Table C-1 can be used as a guide in making such adjustments. For additional information, see Reference 2, Appendix I.

TABLE C–1. Percent increase or decrease in design values for each 1°F decrease or increase in temperature

Property	Moisture content	Cooling below 68°F (Min. -300°F)	Heating above 68°F (Max. 150°F)
Modulus of elasticity	0%	+0.04%	-0.04%
	12%	+0.14%	-0.19%
Other properties	0%	+0.17%	-0.17%
	12%	+0.32%	-0.49%

Regulatory

Code and regulatory officials often adopt the suggested design and products specifications noted above except where regional concerns are paramount, such as earthquake and hurricane loading. To adapt a model code to these special cases, the environmental data base once again is used.

Engineering Practice

The engineering community is responsible for public safety and design performance. But not uncommonly, client needs go a step beyond the standards, specifications, or codes. Yet decisions must be made. Clearly, both tradition and a sound data base are essential, but interpretation is also extremely important. Handbooks and similar documents play a critical role. Examples of wood use in prominent areas where environmental impact decisions must be made include:

Trenching Timber.--Decay hazards. The Forest Products Laboratory, working with the National Bureau of Standards, acknowledged recently the current satisfactory performance of trenching lumber, but suggested use criteria that included the storage period of large green timbers as part of "the design life" because of the decay hazard (Bendtsen and Galligan 1978). The concept of a climate index was used.

Wood Cooling Towers.--Decay, chemicals, temperature, moisture content, and duration of load. Wood is a major structural element in large industrial cooling towers. Design procedures are proprietary, based on available literature plus in-house evaluations. Research on single environment variables hardly touches the complex environment of the cooling tower.

Wood Aircraft.--Decay, duration of load, fatigue. Wood remains an important structural element in powered and nonpowered aircraft. Selection of the wood and its effective application in design depend upon knowledge of its performance in this use.

All-Weather Wood Foundation.--Moisture, decay, load duration. Lumber and other wood products are critical elements. Selection of preservative treatments, fasteners, and associated design assumptions are critical to efficient design and satisfactory performance.

RATIONALE FOR PRIORITIZING ENVIRONMENTAL RESEARCH

If we reflect on the needs of these four types of decision makers, we might conclude that their concerns should be reflected in our research priorities. These concerns include at least three major elements: (1) life safety, (2) short-term structural efficiency, and (3) life cycle costs. I think it is fair to assume, also, that the wood resource will have been served well if these three elements are considered as high priorities in our deliberations.

As an example of how these concerns interact with one another through our "data base," all three concerns *might* find a significant decrease in strength resulting from an effective preservative treatment to be acceptable, *if* such an impact could be sufficiently well documented and controlled.

SUMMARY

All wood researchers active in the areas of moisture content, chemicals, decay, stain, duration of load, and temperature research contribute to a data base that is used constantly to make decisions affecting life safety and other design performance criteria. Those who use the data base have different perspectives and needs; priorities for research should reflect these needs.

The insights we obtain in this workshop by working together in a multidisciplinary fashion must be shared with our peers in an effort to organize and speed research in this important area.

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LUMBER AND ITS USE ENVIRONMENT--RESEARCH NEEDS[1/]

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ABSTRACT

Developing a data base of information on how environmental factors affect design properties of lumber will require research on wood degradation mechanisms, on techniques for detection and assessment of degradation, and on developing quantitative descriptions and models of degradation. The level of degradation that can be tolerated in structures must also be evaluated.

THE NEED

This workshop was organized as a response to five developments and observations that affect our industry:

1. Present grading procedures for lumber appear adequate for many of today's needs. This contention is supported by many years of successful inservice performance by houses built with design and construction methodology similar to those used at the present time.

2. Yet, present knowledge of how enironmental factors affect wood properties is based almost entirely on average trends observed in tests, many of which were made on defect-free small, clear specimens. Recent evidence, based on tests of lumber, indicates that at least some effects are related to lumber size and grade, and may become constant at near-minimum property levels. Other difficulties associated with extrapolating data from small specimens to lumber occur due to size effects, rate of loading differences, and the presence of nonuniformities.

3. Techniques for more refined engineering design are currently being developed. These advanced concepts will require more exact information on the influence of environmental factors on design properties of lumber. They will also require information that will be compatible with a reliability-based design format. While a great deal is known about environmental effects, the necessary statistical information is lacking in most cases.

4. Many environmental effects are so inconspicuous that quantitative information on degradation is not obtainable at the present time. An example of this is decay, where large reductions in toughness can occur at an incipient stage of infestation where detection of fungi or damage even by microscopic examination depends on the "luck" of looking in the right place.

5. Tort law has evolved rapidly to the point where the responsible parties are liable if they lack precise knowledge of how wood products behave in service, should a failure occur.

The purpose of this workshop is to evaluate past literature on how environmental factors affect lumber design properties to determine future research needs, suggest research strategies, and assign research priorities. The ultimate goal of this research is to establish a data base of information that can be used for improved methods of adjusting lumber design properties.

SCOPE

It is not practical or even possible to develop a research program to evaluate all

[1/] Paper presented at the Workshop of Research Needs on Effect of the Environment on Design Properties of Lumber, Forest Products Laboratory, Madison, Wisconsin, May 28-30, 1980.

aspects of the relationship between environmental conditions and design properties. Nor do we have the time to discuss all aspects of the subject at this workshop. Therefore, some boundaries will be set to define our main areas of concern. These boundaries are flexible, and many insights may be gained by going beyond them, where appropriate.

PRODUCTS

Our chief concern is lumber; not only dimension lumber, but material that is five inches or more in thickness with both rectangular (timber) and round (poles and piling) cross sections. Both treated and untreated material will have to be considered for certain uses. We will be looking mainly at softwood species, but hardwoods must also be considered, for example, for cross-ties as well as structural lumber.

This removes panel products and glulam from the mainstream of our discussions. Knowledge gained with these products may be helpful to us, so they are not categorically excluded. Built-up components, whole structures, and consequently fasteners, are also beyond the central focus of our discussions.

ENVIRONMENTAL FACTORS

The environmental factors to be evaluated are temperature, moisture content, biological and chemical factors, and load history. These factors are further subdivided as shown in Table 1. The outline is incomplete in detail, and does not indicate interactions between environmental factors. In general, all factors interact, sometimes in a direct way that lends itself to analytical investigation (temperature-moisture relations), and sometimes in complicated ways that are almost impossible to sort out (temperature-moisture-Carpenter ant population-decay relations).

DEGRADATION RESEARCH APPROACHES

Degradation research must proceed on five fronts in order to provide the desired data base of information:

1. Degradation mechanisms--Additional research into the fundamental mechanisms involved in degradation of wood by environmental factors is needed. Research needs to be less empirical and less phenomenological than it has often been in the past.

2. Degradation detection and assessment--Nondestructive techniques for evaluating degradation are in their infancy, and are not adequate to evaluate incipient levels of damage.

3. Quantitative description of degradation--research must be planned so that degradation rates can be described in terms of mathematical expressions that relate back to the level of concentration of the debilitating environmental factor.

4. Characterization and modeling of degradation--Techniques must be developed and employed to model, hence to predict, degradation over a range of environmental conditions from a limited number of experimentally obtained data points.

5. Degradation tolerance--The level of degradation that can be tolerated in a lumber element without adversely affecting the serviceability of the component or structure needs to be evaluated for a wide range of products and use.

DEGRADATION RESEARCH PRIORITIES

Several questions must be answered before research can begin. How should the five research approaches listed in the previous section be prioritized? What combination of species, products, and properties should be evaluated? What matrix of environmental conditions should be investigated? At first glance the choices seem easy. But, it is important that the right choices be made to efficiently use the limited funds, facilities, and manpower available.

WORKSHOP ACCOMPLISHMENTS

The workshop will make recommendations that will: (1) encourage research efforts on the effect of the use environment on lumber properties; (2) direct research in such a way that results will be as useful as possible for future changes in grading or design procedures; (3) provide a mechanism for coordinating research on as broad a base as possible to maximize research efficiency; (4) provide a climate for communication between researchers; and (5) provide a mechanism for the rapid transfer of technology.

Table 1. Preliminary Classification of Environmental Factors that Influence Design Properties of Wood Products

I. Temperature

  A. Level
    1. High
    2. Low
    3. Cyclic

  B. Effect
    1. Immediate effect
    2. Permanent effect

II. Moisture

  A. Level
    1. High
    2. Ramp drying
    3. Cyclic

  B. Effect
    1. Immediate effect
    2. Permanent effect

III. Chemical

  A. Source
    1. Treatment chemical
    2. Physical contact with source
    3. Airborne

  B. Type of Chemical

  C. Level
    1. Steady-state concentration
    2. Non-steady-state concentration

IV. Biological

  A. Dry Environment
    1. Termites
    2. Beetles

  B. Moist Environment
    1. Decay fungi
    2. Stain fungi
    3. Bacteria

  C. Marine Environment
    1. Marine pests

V. Load History

  A. Sustained Loads

  B. Periodic Loads

  C. Impact Loads

INTERNATIONAL INPUT--REPORT OF LETTERS AND DISCUSSION AT IUFRO S5.02, OXFORD, ENGLAND

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ABSTRACT

The paper quotes from letters sent by invited international partcipants who were unable to attend the workshop and reports on supplemental discussions held at the April 1980 IUFRO 55.02 Wood Engineering meeting.

Introduction

The International Union of Forest Research Organizations' (IUFRO) Subject Group on Wood Engineering (S5.02) met in Oxford, England, this past April for 5 days. During the session on Load Duration and Moisture Content, an invitation to give input to this present workshop was extended to those who would not be here this week.

Interest ran high with the general agreement that international cooperation is necessary. The shortage of time between the IUFRO conference and the International Council for Building Research (CIB) Working Commision on Timber Structures (W18) meeting in Helsinki next week prevented anyone from sending a camera-ready position paper. However, the workshop coordinators had received some letters before the IUFRO meeting, and I will give excerpts from them before adding supplementary points of discussion at Oxford.

Letters

W. T. Curry, B.R.E. Princess Risborough Lab., Princes Risborough, Bucks:

"I am sure that this will be a very worth-while venture at this point in time when we are all in the process of developing a new approach to the problems of determining and specifying design stresses for lumber.

"Testing timber in structural sizes is expensive and time consuming, just the situation where harmonisation is needed if we are to be able to make maximum use of the accumulated information, both nationally and internationally. For many countries who import North American timber it will be necessary for them to interpret this information in relation to their own national design codes, and it would be unfortunate if this becomes impossible because of diverging approaches. In designing test programmes it is also desirable to recognise that current grading systems are not static, and that the response of lumber to environmental factors may not be the same for visually graded and machine graded lumber. We should therefore try to record sufficient data, and to design our sampling and test procedures, so that the results are not restricted to an inflexible interpretation.

"Currently it would seem that North America is approaching the problem of product evaluation by changes in testing methods (proof loading at very rapid rates and concentration on distribution tails) to permit more samples to be tested. This raises the need to calibrate these new methods with the experience and confidence gained with the old methods. For example what is the real significance of a 5 percentile stress from structural size tests compared with a corresponding stress obtained from a 5 percentile small clear specimen stress."

L. G. Booth, Imperial College of Science and Technology, London, England:

"I consider the aims of your meeting to be very important and I consider the problems are so large that a coordinated research

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[1]Paper presented at the Workshop of Research Needs on Effect of the Environment on Design Properties of Lumber, Forest Products Laboratory, Madison, Wisconsin, May 28-30, 1980.

programme will be essential if we are to make significant progress in the forseeable future.

"You may however find the attached report of interest: your particular problems are mentioned but not in depth due to the scope of publication."

The following seven paragraphs are from a discussion document entitled "Future needs of timber research in the U.K.:"

"34. There is a general shortage of information on load deformation characteristics of joints and very little is known about their long-term behaviour under load. There is a particular need for basic design data for nailed/glued assemblies.

"36. The performance of timber in buildings is dependent not only on its structural properties but also upon the conditions (particularly moisture) which surround it. Changes in design, material usage, levels of heating, thermal and sound insulation etc have all contributed to varying the service environment in which the timber exists, particularly in the external envelope of the building. These changes need to be better understood and guidance given in codes so that the factors are adequately considered at the design stage.

"46. Not all the properties which affect the use of timber will be considered here but only those for which further information needs to be sought. A considerable body of information already exists and more recently an attempt has been made to relate this more directly to end-use requirements. Thus the properties needed for certain end uses have been defined, and timbers and board materials classified accordingly.

"47. Duration of load effects (including creep) were considered to be a particularly important aspect requiring research. The extensive amount of test work necessary to derive satisfactory strength data makes such a topic well suited to international cooperation, and a programme has recently begun to assess the moisture and duration of load effects on structural timber.

"51. The subject of the movement in service of timber and timber products merits further investigation. Such effects may well be aggravated by current trends towards higher demands for thermal comfort. Whilst much of this can be attributed to incorrect moisture content at the time of installation, there may be additional long-term stress relaxation phenomena involved, eg the effect of drying history on the movement of timber in service.

"52. The inter-relationship between timber products and moisture is considered fundamental to their utilization, and a better understanding of its characteristics and control is essential. The creep of individual materials and built-up timber components under high and varying moisture content needs to be quantified and studies carried out on means of reducing the effect.

"53. The propensity of timber to absorb moisture can have a significant effect on the durability of timber-based products out of contact with the ground. Ways of reducing this either through the natural physical properties of timber or through applied treatments (eg water repellents) need to be explored."

N. I. Bovim, The Norwegian Institute of Wood Working and Wood Technology, Oslo, Norway:

"We have done some work on the influence of the moisture content on strength and stiffness of structural timber and fingerjointed timber. Some of the results have already been presented in the CIB/IUFRO working group: Time and Moisture Effects."

T. Nakai, Forestry and Forest Products Research Institute, Ushiku, Ibaraki, Japan:

"As we are now frequently asked to predict the long-term in-service response of wood bearing walls in two by four (platform) construction together with Japanese conventional wood frame houses, which may be said as a kind of post and beam construction, due to the usage of much insulation material in wooden houses becomes very popular and has been encouraged by the authority for saving energy. Biological degradation, however, had been observed inside of bearing wall and flooring when insulation materials were used. This could be caused by condensation. We are very interested to know the condition at which condensation would not take place and insulation works well. The very limited survey had conducted around Tokyo area and Hokkaido. Then a small facility with measuring system for relative humidity and temperature had been installed to conduct a series of model test on full size wall (approximately 6' by 6'). We are now making a plan of condensation test for various condition."

J. Ehlbeck, University of Karlsruhe, Karlsruhe, Federal Republic of Germany:

"The idea of establishing a workshop to conduct a systematic evaluation of research needs is much recommendable with the aim in mind to come to international agreements and to advance international cooperation in evaluating design properties of lumber. I am sure that there are some European Institutions interested in such a coordination of research needed, e.g., in Scandinavia, UK, and the

Netherlands. Although our special research efforts here in Karlsruhe, University of Karlsruhe, Fed. Rep. of Germany, are concentrated on structural problems with wood as well as glulam constructions and on mechanical fastener systems usable for wood structures and assembly, we are, of course, interested in all items mentioned as background and purpose of the workshop under discussion. Especially problems of static and long term effects concerning the correlation between strength and deformation behavior of small clear specimens and full size structural lumber, are of interest to us. Such research efforts may also provide further information on both the ultimate load carrying capacity and the creep under long term loading of joints."

P. Hoffmeyer, Technical University of Denmark, Lyngby, Denmark:

"The idea of having a workshop as suggested is excellent considering the growing interest in the influence of environmental factors on the properties of structural timber.

"For your information, we are still involved in studies of duration of load- and moisture factors of lumber. A theoretical study of duration of load is near completion. We plan to translate much of the work into English and a copy will be forwarded to you when completed. As you may recall the theory is based on a synthesis of fracture mechanics and viscoelastic theory of elasticity. The theory is now being tried out on a large series of bending tests including small clear notched specimens. Next year we hope to start full size duration of load tests in order to link the theory to dimension lumber.

"The influence of different moisture content levels on duration of load is also being studied closely and we are rather optimistic about this too."

J. Kuipers, Delft University of Technology, Delft, Netherlands:

"I also made a start to write down some views about what I think is necessary in our (small) part of the world in the field of research needs in the direction of the interest of your workshop.

General Remarks About the Research Needs on the Effect of the Environment on Design Properties of Lumber;

Different needs in different parts of the world.--Since there is a wide diversity in the availability and the use of wood in different places also the direct need for development and research will vary considerably. As an example: in our country the amount of wooden house is very small and timber frame construction has just started. We therefore have to give very basic information to architects and builders to avoid mistakes which could harm the image of this timber use. This, I think is a problem of quite another character than in your country and it gives rises to another view on the problems:

- We don't use sawn timber so much as you for studs flooring and roof trusses or trusses rafters. The need for strength grading therefore is only limited and 'appearance-grading' for many different end uses is a much more primary interest.

- Much timber is used for windows and windowframes, doors and door frames, etc. Here much attention has been paid to the structural details, manufacturing and machining. The problems we had with wood decay some 10 to 15 years ago seem to have disappeared now. New demands with respect to lower energy-consumption bring forward new structural details and therefore changes in the climate around these timber structures may occur.

I think that better methods should be developed to design and calculate structures and structural parts for a 'loading' by moisture and temperature. We therefore need much more knowledge about the already mentioned micro-climatic conditions around these structures and about the damp-diffusion characteristics of the wood in combination with salants (sealants), paints, etc. This means also that the user should be informed as precise as possible about methods and means to maintain these well-designed parts of craftsmanship to avoid decay and to keep it in a good appearance. Manufacturers should provide the user with a maintenance-scheme.

Usefulness of other wood species.--The possibilities of the different softwood species are well known and its properties are estimated in a positive manner. Nevertheless, generally the durability of this wood is limited and in most cases the possibility to impregnate it with decay-resistant agencies is poor.

Could there be developed other wood species that combine the positive characteristics of these softwoods with better durability or easier to treate effectively with fungicides? This, may be, could also lead to more variety in the softwood forest regions. In this respect I am thinking about species like birch, poplar, alder, etc., fast-growing with

acceptable strength properties, relatively easy to treat with fungicides.

Do we know however what the effectiveness is of certain treatments? Can we predict the durability of untreated and of treated wood in certain circumstances?

Duration of loading.--We have to know much more about the effects of load duration on wood and connections including glue and glued products. Effects of permanent loads, repeated loads, fatigue loads, loads with changing direction (especially for joints), etc. We did work in this direction since ca. 1960, especially on joints.

Development of wood products.--Methods should be developed to manufacture from wood particles with smaller or greater dimensions, products:

- with free dimensional forms: sheets, profiles, tubes, etc.,

- where the wood is impregnated by the decay-resistant binder (glue, cement or?),

- where 'no' creep occurs;

- with strength values, dependent from the amount of binder, pressure, etc. but may be also from an amount of extra glass fibres, steel fibres or . . .?

The durability, moisture sensitiveness, strength and creep of many sheet materials are at this moment not very satisfactory for the use in load bearing structures.

Effect of fire on joints.--In recent years the knowledge about the behaviour of wood in fire has grown considerably but not about the joints. More information is needed, resulting in possibilities to design and calculate complete structures.

In our country a method was developed to design a timber cladding around steel columns as a protection against fire.

Effect of the 'technical environment.'--The image of wood as a structural material is what the architect and the structural engineer think about it. Especially the developments in steel and concrete have lead to large and impressive structures. Because we all are impressed by great dimensions this means that timber, used for structures of more modest dimensions give the impression that they are of less importance and theoretical interest. We have therefore to convince specialists e.g. in applied mechanics, that they don't compromise themselves if they pay attention to wood. In this connection it seems important to me that e.g. a part of the coming IABSE-congres in Vienna is dedicated to timber structures. It might be worthwhile to consider if much more information about interesting problems and solutions could be published in journals, generally read by structural engineers. I think that only very few of them read Forest Products Journal or the Wood Science, etc."

B. Noren, Swedish Forest Products Research Laboratory, Stockholm, Sweden:

"You know, of course, that we are interested in cooperation of this kind, not the least with respect to time and moisture effects on lumber strength. I hope a discussion can be arranged on this subject in connection with the IUFRO Div. 5 Conference next month."[1]

IUFRO S5.02 Session on Moisture Content and Load Duration

Discussions at IUFRO included points contained in the letters, but additional points were also brought up at the session on Moisture Content and Load Duration. After presentation of the proposed U.S. and Canadian research on load duration of structural lumber, the discussion surfaced the following comments: (1) There should be variable environment conditions and stress histories on more than one species in more than one testing mode (i.e. not just bending), (2) load duration information on mechanical fasteners is needed, and (3) information on material selection and sample size for load duration research is urgently needed.

CIB W18/IUFRO S5.02-3 Time and Moisture Effects Group

Bengt Noren's suggestion (in his letter) led to a convening of the CIB W18/IUFRO S5.02-3 Time and Moisture Effects Group. At the meeting it was agreed that the group is useful for an exchange of views on the stated subject areas and that we should channel information through te group chairman (i.e. Bengt). Also a suggestion was made that perhaps Europe could complement the U.S. and Canadian load duration lumber research by investigating the load duration phenomena of mechanical fasteners (e.g truss connectors).

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[1]This suggestion led to a separate discussion group after the S5.02 session on Moisture Content and Load Duration.

Summary

In summary, IUFRO participants thought the workshop was timely and showed genuine international interest with a willingness to cooperate. We should maintain the foster contacts for international cooperation and communication through established international groups such as CIB W18/IUFRO S5.02-3.

USE CONDITIONS FOR WOOD--THOUGHTS FROM THE ADVERSE ENVIRONMENTS SYMPOSIUM

By

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Abstract

Use conditions for wood include a broad range of possible conditions, some of which have deleterious effects on its engineering properties. This paper contains highlights of review papers on effects of adverse environmental conditions on use of wood.

INTRODUCTION

This paper is a summarization of invited review papers presented at the SWST Symposium, Structural Use of Wood in Adverse Environments. A listing of these papers is given in Appendix 1. Although this paper is a summary of review papers, literature references are given only for Tables and Figures adapted from original sources by the reviewers. It stresses use conditions for lumber, and does not discuss the repair techniques presented at the Vancouver meeting.

The range of adverse environments to which structures are subjected is probably limited to extreme ranges of temperature and moisture content, with chemicals, stress levels, and loading histories superimposed. That is, reasonably expected temperature and moisture content extremes might range from -50 to +100°C and 0% MC to saturation.

Many chemicals in addition to those naturally present in wood might be present. Wood preservatives or fire retardants might be introduced into the wood or a host of chemicals from the environment of the structure may come in contact with the wood. Each of these factors, temperature, moisture content and chemicals, can interact singly or in concert with time and stress level until deterioration or even failure of one or more members of a wood structure may occur.

MOISTURE CONTENT, TEMPERATURE, CHEMICAL EFFECTS

Atmospheric conditions in structures may induce moisture contents close to zero, thereby allowing appreciable drying of wood in service if the moisture content at time of installation was in the 15 to 19% range commonly found in commercially dried structural lumber. Increased stiffness due to drying may be considerably offset by the reduced section modulus due to shrinkage, so the bending stiffness of beams may remain essentially constant during drying. However, drying defects introduced during this uncontrolled drying will introduce some uncertainty in structural performance of the wood. An example might be drying defects induced in a rafter or the upper chord of a roof truss just below a south-facing roof covered with black asphalt roofing on a hot summer day. Depending on original moisture content and presence of defects already present, additional defects due to seasoning could reduce load-carrying capacity of the wood member.

The generally accepted relation between moisture content and strength is that reduced moisture content results in higher ultimate stress, higher stress at proportional limit, higher modulus of elasticity, and less deflection for a given stress level. Most mechanical properties, P, follow a negative exponential relationship with moisture content, M, below the fiber saturation point:

$$P = Ae^{-BM},$$

where A and B are constants related to the wood species and property being considered. However, such properties as toughness and work in bending, in which deflection and force interact, may not be affected by moisture content due to offsetting effects of moisture on stiffness and strength measurements.

Short-term testing of wood heated to various temperatures and tested while heated demonstrates a continued decrease in strength with increase in temperature starting at relatively low temperatures until, at temperatures of about 300°C, the compressive and tensile strengths are reduced to about 0.2 of the strength at 25°C, with a greater decrease for compressive than for tensile strength (Fig. 1). Inflection points demonstrate

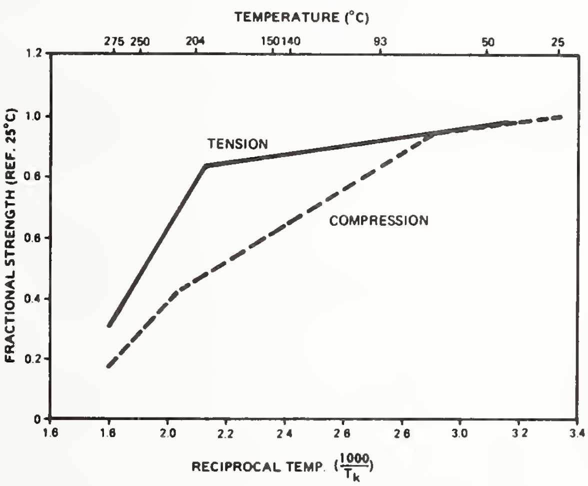

Figure 1. Immediate modulus of rupture of ovendry Douglas-fir parallel to the grain, tested at the indicated temperature (adapted from Schaffer 1970 by Beall).

various microstructural changes for some of the wood constituents. The effect on toughness and impact bending is even greater, and the effect on elastic modulus somewhat less. Loss of tensile strength has been shown to be sensitive to heating medium and/or presence of oxygen, so specific heating conditions must always be considered for either experimentation or the use environment of a structure.

Several studies have measured wood strength at low temperatures. Results must be evaluated in relation to presence of free ice for studies above the fiber saturation point, possible changes in phase for sorbed water at moisture contents at or below the fiber saturation point, and reductions in cell wall moisture content if ice forms in lumens rather than in cell walls for moisture contents below the fiber saturation point. Maximum crushing strength increases linearly as temperature decreases from 200 to -191°C. Shear strength also increases as temperature decreases, but goes through a peak near -70°C, and then decreases down to -183°C (the lowest temperature studied). When shear samples fail at low temperatures, the failure is a catastrophic explosion, due to brittle intracellular failure. An anisotropic effect on shear failure at low temperatures causes shear angle to increase directly with temperature, probably because radial stiffness is more temperature sensitive than longitudinal stiffness when tested at 12% moisture content. This effect was not observed when moisture content was 190% for tests at 20 and 105°C.

Balsa wood linings have been used for liquid natural gas tankers for over twenty years, a use environment at cryogenic temperatures (-162°C) where the wood is exposed to compressive and shock stresses. Extreme low temperatures (-184°C) apparently do not adversely affect plywood strength. Commercially-made 3-ply oriented particleboards have a strong positive correlation between toughness and temperature in the range -29 to 82°C. Graded density and 3-layer boards had much less response to low temperatures. Type of furnish and relative board strength probably also affected results. Low temperature effects have not been well documented for all wood products.

There is a decided interaction between the effects of temperature and moisture on wood strength. The originally linear relation between temperature and elastic modulus becomes increasingly curvilinear as moisture content is increased (Fig. 2). As moisture content is increased beyond 12% and temperature is raised above 60°C, the rate of decrease in MOE becomes precipitous. Below freezing, stiffness increases if moisture content is increased well above fiber saturation point, probably due to stiffness of the ice in lumens (Fig. 3).

Cyclic exposure to changes in moisture content have been shown to greatly reduce wood strength, leading to creep failure at loads only 3/8 the maximum load a similar wood specimen should sustain if held at a constant moisture content (Fig. 4). If wood is maintained at a constant low (less than fsp) or constant high (above fsp) moisture content while under load, and the moisture content is suddenly increased or decreased, respectively, creep increases. For the specimen whose moisture content is increased, creep failure occurs if bending stress is about 0.4 or more of the short term strength (Fig. 5). These effects suggest we must be concerned about cyclic effects of moisture content, and prob-

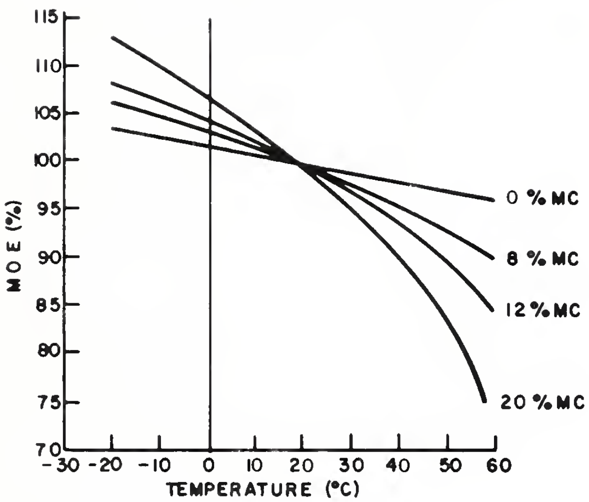

Figure 2. Relative average modulus of elasticity of six species of wood affected by the temperature-moisture interaction (adapted from Sulzberger 1953 by Bodig).

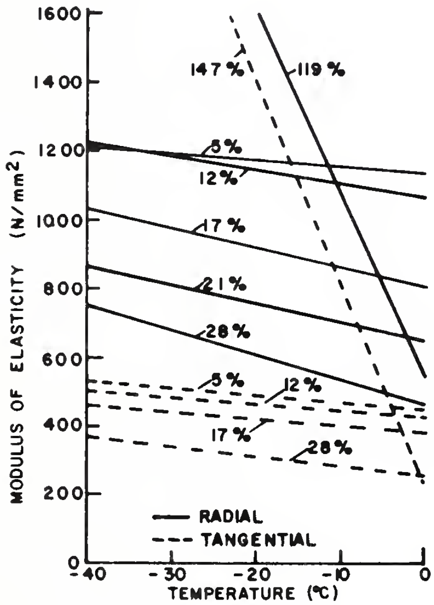

Figure 3. Relationship between transverse tensile moduli of elasticity of spruce and temperature at different moisture contents (adapted from Noack and Geissen 1976 by Bodig).

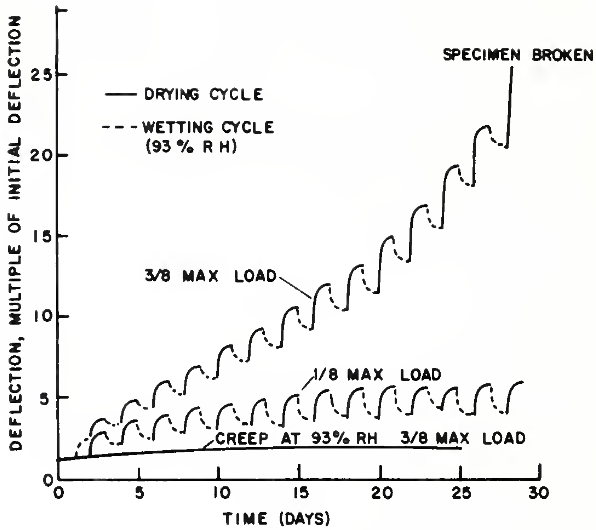

Figure 4. Effect of cycling relative humidity on the creep behavior of beech in bending (adapted from Hearmon & Paton 1964 by Bodig).

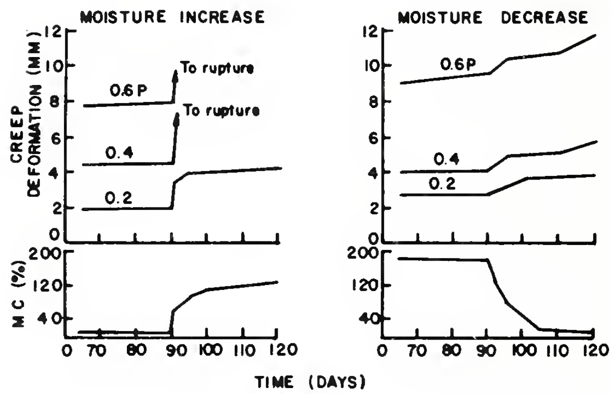

Figure 5. Effect of sudden changes in moisture content on the creep of pine in bending under 0.6, 0.4, and 0.2 fractions of short-term strength (adapted from Raczkowski 1969 by Bodig).

ably also temperature, if wood members are continuously stressed to more than perhaps one quarter of their short-term strength.

The effect of acids and bases on wood strength is greatly influenced by wood species (Table 1). Hardwoods are generally more susceptible to chemical degradation than are softwoods, and the southern pines are more resistant than other softwoods tested. At similar concentrations, alkalis have a greater effect on wood strength than do acids. Acids reduce strength and make the wood more brittle, de-

Table 1. Retention of MOR and work to maximum load of wood species exposed to HCl and NaOH

Species	Chemical and Concentration	Modulus of Rupture		Work to Maximum Load		Reference
		20°C	50°C	20°C	50°C	
Caribbean Pine	2% HCl	102	75	90	48	Wangaard 1966
	10% HCl	72	60	71	56	
	2% NaOH	65	53	80	65	
	10% NaOH	53	37	77	51	
Douglas-fir	2% HCl	91	85	57	34	Wangaard 1966
	10% HCl	76	57	38	33	
	2% NaOH	56	40	72	53	
	10% NaOH	39	28	69	53	
Eleven Hardwoods	2% HCl	87	70	69	45	Wangaard 1966
	10% HCl	56	42	28	22	
	2% NaOH	39	32	53	44	
	10% NaOH	25	22	41	36	
Four Southern Pines	2% HCl	98	86	91	44	Thompson 1969
	10% HCl	79	67	43	35	
	2% NaOH	66	75	79	74	
	10% NaOH	54	57	68	53	

Source: Thompson, W. S. Adverse environments and related design considerations--chemical effects.

pending on acid concentration, exposure time and temperature. Alkalis dissolve some of the hemicelluloses and attack lignin. Alternate exposure to acids and bases is a most severe service condition. Increases in temperature of 10 to 12°C double the rate of chemical attack. If pH of solutions to which wood must be exposed can be kept to within 3 to 7, the wood will apparently remain unaffected. The greater susceptibility of hardwoods to chemical degradation relative to softwoods suggests a need for research on structural applications of hardwoods in adverse chemical environments--including both solid wood and composite products.

In contrast to acids and bases, some salts may significantly increase certain strength properties, such as maximum crushing strength. Sodium carbonate solutions (2-6%) can greatly reduce strength, while members of a series of chloride salts have been shown to increase maximum crushing strength of red pine. The oxides or acid salts of copper, chromium and arsenic apparently do not reduce strength. However, improper drying of CCA-treated poles can reduce their strength.

Steaming alone can markedly reduce strength of poles. For one study using southern pine poles, shock resistance was reduced 60%, MOR was reduced 44%, fiber stress at proportional limit was reduced 42%, and MOE was reduced 22% when steamed 16 hrs. at 300°F. Douglas-fir and Engelmann spruce underwent similar reductions. Numerous studies have demonstrated these types of reductions, which can be similar to a mild acid hydrolysis. The entire seasoning-preserving sequence must be studied carefully so strength reductions due to various production variables can be predicted accurately, especially for salts-type preservatives, but for other preservatives as well. Numerous areas for additional research include estimates of the amount of strength reduction that can be tolerated due to seasoning practices; degradation, usually biological, that occurs during storage; effects of mechanical handling methods; effects of creosote treatment methods on wood properties; and which mechanical and physical

properties are [illegible], such as static bending [illegible] toughness, hardness, etc.

Rusting iron [illegible] reductions in tensile strength of moist wood. The amount of strength reduction becomes [illegible] after only a few weeks but continues for many months for prolonged exposure. These effects are apparently due to oxidation and depolymerization of both cellulose and [illegible] so that not only cell wall microfibrils [illegible] materials are being degraded. Although sapwood is affected more during the first [illegible] months, after nine months, there was no significant difference between sapwood and heartwood. Compressive strength does not [illegible] to be affected. Green or partially seasoned southern pine in contact with nails suffered cellulose deterioration even though the wood was not discolored, so the extent of this type of damage may not be realized, with analysis of failure made extremely difficult.

Salt-type preservatives generally promote deterioration of metal fasteners, while creosote treatments reduce [illegible]. The specific effect of salt-type preservatives and fire retardants on corrosion of metals [illegible] varies with the preservative involved. Serious corrosion can occur when moisture content exceeds 15%.

The interaction between chemicals present, temperature and moisture content is typical of chemical reactions. When chemicals and fasteners are present, it is important to be sure moisture content is [illegible] and, if possible, temperature as well. Research continues on fastener-wood-moisture content interactions.

WEATHERING AND BIOLOGICAL EFFECTS ON WOOD IN [illegible]

Weathering

Wood exposed to the weather roughens as checks develop, earlywood is eroded, and grain raises. In intense sunlight, wood color changes rapidly as ultraviolet radiation causes first a darkening and then a graying of the wood due to degradation of lignin. In addition, dirt may accumulate on the surface, susceptibility to abrasion increases, and if sufficient moisture is present, stain due to mildew and staining fungi can develop.

Weathering is a surface phenomenon. Physical changes due to ultraviolet radiation penetrate less than one millimeter. Checking due to repeated wetting and drying of the surface from rain, dew, and high humidities is generally limited to the surface where moisture gradients are most severe and stresses due to moisture change induce and then extend the checks.

Loss of wood due to weathering is slow, but can be significant for either thin pieces of wood over decades or structural pieces over centuries. That is, reported erosion rates have varied from 1, 6, and 13 mm per century. These rates can have structural significance, demonstrated by one estimate of a reduction by half in thickness of 10 mm-thick cladding over a few hundred years.

Good design and construction practices to protect wood from prolonged wetting and use of finishes to protect from ultraviolet degradation should essentially eliminate weathering as a cause for failure of wood in structural situations.

Biodegradation

Wood, being a biological material, is susceptible to degradation by organisms that wish to use it as a food source or as a nesting site. Bacteria and fungi induce a biochemical attack while insects mechanically remove small bits of wood. Bacteria require water for mobility, and thrive when wood is saturated with water, as in piling or water-stored logs. Decay fungi require far less water, growing best in wood with moisture contents ranging down to just above fiber saturation points. Molds can grow on air-dry wood if relative humidity exceeds 80%. Insects have a range of moisture content preferences, from the high moisture content of green wood (large wood borers), to "damp" wood (termites and carpenter ants), to very low moisture contents (dry wood termites and lyctid beetles).

The initial effect of a bacterial attack on wood is generally considered to be an increase in permeability, but it can also slightly decrease toughness with no change in specific gravity. Sapwood of all species is susceptible. The increase in permeability makes bacterially-degraded wood especially susceptible to increased moisture absorption from rain impingement. Reductions of 50% in crushing strength parallel to grain have been observed in pilings submerged 62 years at Washington, D. C.

Wood decay fungi can cause severe reductions in wood strength at only modest weight losses. Brown-rotted wood loses strength faster than does white-rotted wood. At equivalent weight losses, white rot fungi cause similar strength losses in various wood species. Brown rot fungi, however, cause different strength reductions in different wood species. In some cases, MOR and work to maximum load in static bending were reduced drastically even though little or no weight loss was observed.

Brown rots are responsible for the major losses in strength of softwood construction timbers. Table 2 summarizes potential strength reductions of brown-rotted softwoods at only 5-10% weight loss. It must be stressed that the normal variability between and within trees of the same species would mask a weight loss of only 5 to 10%.

Table 2. Strength reductions due to weight losses of 5 to 10% measured in brown-rotted softwoods

Strength Property	Expected Strength Loss (% of sound wood strength) percent
Toughness	80+
Impact bending	80
Static bending (MOR & MOE)	70
Compression perpendicular	60
Tension parallel	60
Compression parallel	45
Shear	20
Hardness	20

Source: Wilcox, 1978. Wood and Fiber 9(4):252-257.

Since this low level of decay is essentially undetectable, implications of these large reductions in strength for minor amounts of decay are great for wood to be used in critical load-bearing situations, especially where shock or impact loadings are expected. Implications are equally great in planning research projects to test effects of use environments on design properties of lumber when assurance must be given that the lumber is free of decay, especially if a testing regime should involve moisture contents of 20% or more.

Stain fungi are generally disregarded as strength-reducing wood inhabiting organisms. However, when blue stain is fully developed in a piece of wood, it may reduce specific gravity by 1 to 2%, which is an undetectable amount, but toughness might be reduced 15 to 30%. Decay fungi are often present, so the potential for additional strength reductions is real. Because stained wood often has increased permeability, it can absorb more water when it is exposed to rain, which could increase its susceptibility to decay.

Temperature of wood in use does not appear to limit the potential for decay, but if decay has started, the rate at which it proceeds is increased as temperature increases to an optimum value near 35-40°C. The general assumption is that wood with a moisture content below 20% is safe from decay and that if moisture content exceeds 30%, preservation is definitely required. However, some thermophilic soft-rot fungi growing in exterior wood subject to heating by insolation can grow in wood with a moisture content less than 20%.

In addition to these thermophilic fungi are molds that can grow on wood if relative humidity exceeds 85%. Wood EMC at 85% relative humidity is less than 20%. Such a relative humidity is achieved in many structural situations, especially when large temperature gradients exist across walls. Although molds are normally considered to be only appearance defects for solid wood, they often do affect the physical properties of wood. Ability of molds to increase wood permeability by destroying ray cells has been recognized for many years. In the case of particleboards and fiberboards, the molds have far more severe strength-reducing effects. In some cases, strength reduction can be measured with no weight loss, suggesting that the wood-adhesive bonds are attacked. In other cases, weight losses occur resulting, in the case of fiberboards, in strength losses of 50%. Increasing use of particleboards and fiberboards for structural applications indicates the need for more research into effects of molds on structural performance of these products and on moisture content profiles of structural systems when vapor barriers, amounts of insulation, mechanical humidification, and temperature gradients interact.

Currently, when average January temperatures drop below about 35°F, vapor barriers are recommended for residential construction. This zone covers over half of the United States (Fig. 6). As retrofit insulation is applied to older homes with no vapor barriers, and as increased amounts of composite wood products are used in new construction with thicker layers of insulation, the opportunity for biodeterioration increases rapidly.

Structural failures due to wood decay are too often design and maintenance related. Besides the vapor barrier and insulation problems just mentioned are moisture content increases that occur when rainwater enters a structure due to inadequate flashing detail, flow of rainwater over wood end grain with resultant rapid increase in moisture content, plumbing leaks, condensation, ventilation inadequacies, failure to use vapor barrier ground coverings in crawl space construction, etc. Numerous

Figure 6. Regions where winter condensation problems require use of vapor barriers for new construction and structures to which retrofit insulation is added (Anderson and Sherwood 1974).

design, construction, and maintenance problems result in high wood moisture contents leading to more wood decay situations than can be considered in a short review.

Although termites are found in most parts of the United States, they reach their greatest level of development and virulence in the southern states, especially the warm, moist southeast, where careful attention to specific structural designs and construction practices to protect wood is required. Preservative treatments for both decay and termite resistance, as well as use of termite shields, adequate clearance from the ground, and site sanitation do not guarantee protection from attack, especially for untreated wood placed adjacent to either preservative-treated wood or physical barriers. If termite danger is high due to presence of termites on or near building sites, then soil poisoning is required to ensure protection, provided the poisoning can provide a complete envelope around the structure. Use of bait blocks to induce termites to feed on insecticide-treated wood may keep the insects in check, providing another method of protection. Use of naturally repellent woods may provide control in some situations, with additional efforts needed to determine the chemical structure of these repellents and the possibility that they might be used as treatment chemicals.

A class of wood biodeteriogens often overlooked is the marine borers. These animals cause over one-half billion dollars damage each year in the United States alone, with far greater destruction occurring in other parts of the world. One problem in evaluating the extent of damage is the difficulty in classifying causes of failure as being due to marine borers, marine decay fungi, mechanical damage, or combinations of these. When final failure is mechanical, the underlying cause of breakage may be due to fungi or borers. Proper treatment of wood used in marine structures is essential. Since at least one borer, Limnoria tripunctata, tolerates creosote, the type of borers to be guarded against must be considered so that creosote, salts, or salts-creosote dual

treatment can be selected as appropriate. Even when treated materials are used, waterfront structures must be inspected and repaired continually, with degraded members replaced before serviceability of the entire structure is reduced. Records on type of damage (mechanical, biological, or a combination), frequency of repair, species of wood used and type of treatment should point out areas for research to improve existing practices for maintenance and repair as well as species and preservative selections to be used. Research on naturally resistant timbers may lead to new treatment chemicals and methods.

TIME EFFECTS

Effects of loading time on wood structures must take into consideration load history. Factors to be included in the history would be maximum stress achieved and time at maximum stress, or a time-weighted stress history, degree of cyclic loading, cyclic moisture contents while under load, excursions in temperature, and the potential for occurrence of biodegradation, usually as a result of moisture contents over about 20%.

Loading time studies generally consider rate of loading, using an arbitrary time-to-fracture of 5 min. to standardize test results. Separate constant load data is needed for creep evaluation. Green wood generally has a greater load-duration effect than does dry material (Fig. 7). Loading rate has the

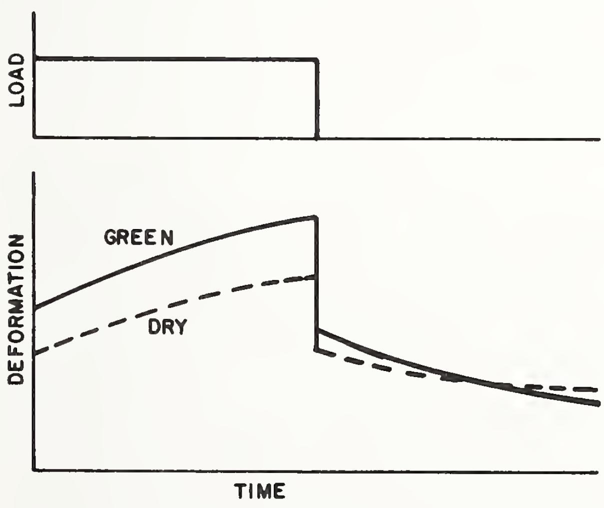

Figure 7. Qualitative effect of moisture content on creep behavior of wood (Bodig, Fig. 9 in symposium paper).

greatest effect on tension strength perpendicular to grain, somewhat less for bending and compression strength, and still less for shear strength. Elastic modulus is affected by rate of loading to a relatively small degree.

Various load-duration studies have been summarized into the hyperbolic curve generally accepted to determine design loads for wood members, using 10 years for "normal" duration of full design load in a wood structure (Fig. 8).

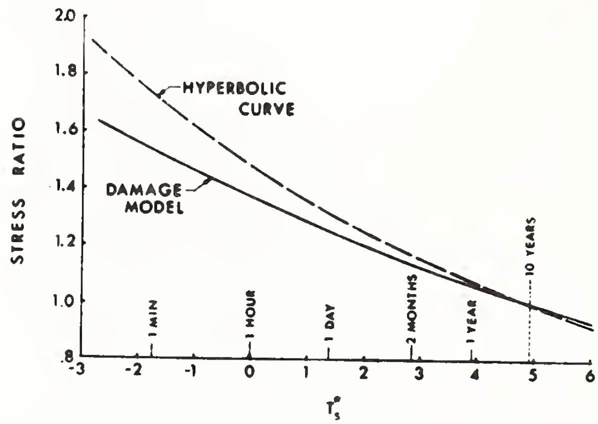

Figure 8. The hyperbolic curve relating design stress to stress corresponding to normal 10-year duration as obtained by Wood (1951) for constant loads and the damage model curve of Barrett that accounts for cyclic loading effects (Barrett, Fig. 8 in symposium paper).

This curve was developed using small clear specimens under constant environmental conditions. The effect of cyclic variations in moisture content mentioned earlier (Fig. 4) drastically reduces time to fracture for small specimens, so the specimens loaded to 3/8 and 1/4 of their short-term strength failed in 28 and 76 days respectively. For larger specimens a 24 hr. cycling of relative humidity from 35 to 93% demonstrated that large specimens (2 in. sq.) are not nearly as affected as smaller specimens (1 cm high, 2 cm wide) (Fig. 9). Small members, especially thin sheet materials, may be adversely affected by relative humidity cycles, but dimension lumber may not be.

Interaction between moisture content and temperature affects stress relaxation in a nonlinear fashion (Fig. 10). Since the effects of increased moisture content are greater at higher temperature, any cyclic changes in relative humidity or moisture content will be exaggerated if the wood member is at a greater temperature. Although this interaction can be exploited to advantage for steam bending of wood, it may have

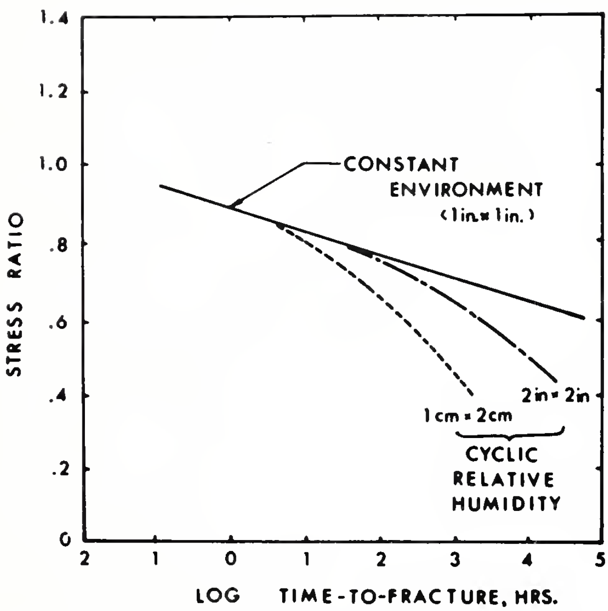

Figure 9. Effect of cyclic relative humidity exposure on time to fracture for small clear bending specimens (Barrett, Fig. 9 in symposium paper).

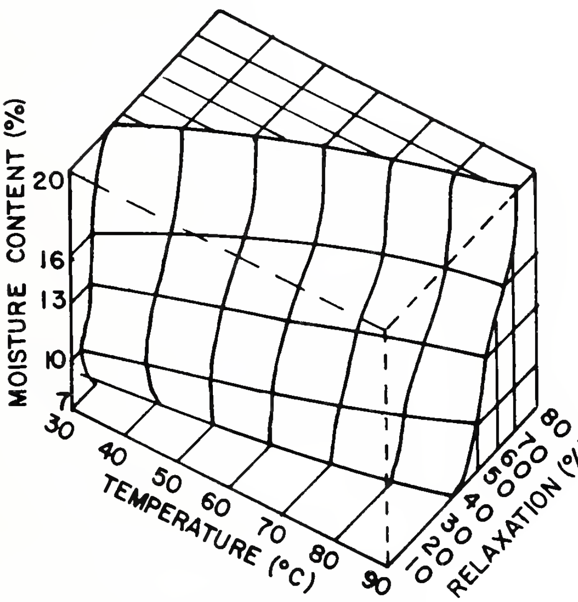

Figure 10. Interaction between temperature and moisture content measured by stress relaxation in 48 hours (adapted from Becker and Reiter 1970 by Bodig).

an adverse consequence for some applications, such as in cooling towers, industrial tanks and pipes, or near process machinery operating with hot, wet materials. The specimens used to generate data for Figure 10 were 18 mm by 66 mm in cross section, 240 mm long, and were tested as a cantilever beam with relaxation measured over only a 48-hour period. More research on effects of cyclic exposures are necessary for the greater temperatures shown in Figure 10.

The effects of specimen size on time to fracture shown in Figure 9 illustrate how the general applicability of the hyperbolic curve to anything but the small clear specimens it was designed for must be questioned. In addition, the complete load history of test specimens and structural members must be described accurately.

Various types of models are being proposed to predict time-to-failure of wood specimens given various load histories. Before final models are chosen, it will be necessary to develop ramp load and constant load information for various important structural wood products and for various mechanical properties. It must be recognized that data on the entire load history must be gathered rather than assessing only maximum loads. Accurate prediction of structural reliability will follow from such load-strength models provided load history, environmental conditions, the relationship between applied load and member stress, and an accurate description of the entire load history, are all known.

Designing for adverse structural environments runs the gamut of such long-term constant effects as weathering, biodegradation, and long load durations through cyclic effects of relative humidity, loading, etc., to short-term severe loading due to flood, tornado, earthquake, etc. Total annual property damage due to natural hazards demands research to ameliorate these losses (Table 3).

The hyperbolic damage model traditionally used for codified structural design procedures tends to overdesign wood structural members for short-term loading due to these natural hazards. Fastener details are often inadequate to resist short-duration stresses that either exceed the design load or are exerted in directions different than expected for normal design loads. Examples are foundation anchors to resist earthquake or use of various types of framing anchors to resist uplift due to tornado or hurricane-force winds. Shear stresses in members and stress concentrations at connections often lead to failures. Comprehensive attention to design details such as use of compartmental design and better connectors can greatly increase structural integrity; connectors are the weakest links in

Table 3. Typical annual United States loss in 1970 dollars for 9 natural hazards (from Wiggins 1977)

Ranking	Hazard	Origin	Loss $\$x10^6$
1	River Flood	Water	1900
2	Expansive Soil	Land	1100
3	Tornado	Air	880
4	Hurricane	Air	685
5	Earthquake	Land	620
6	Storm Surge	Water	440
7	Landslide	Land	210
8	Tsunami	Water	15
9	Severe Wind	Air	11

most timber designs. Not only upgrading existing buildings but also new design detailing must be studied and applied.

STRUCTURAL DESIGN

As design methods for structures begin to utilize such techniques as limit states design, the effects of all potential environmental conditions will have to be considered. Present design codes deal with usual structural environments, with factors assigned for wind, snow, seismic or long-term load effects, but other extremes in the environment, such as changes in material properties due to variations in temperature, moisture content, or changes due to weathering or chemical degradation, are not adequately dealt with.

Limit states design procedures, for example, define the important limiting factors that affect serviceability of members and structures, so suitable margins of safety can be used to determine structural design. If load histories and effects of the environment, such as temperature and moisture content fluctuations, are used to determine a cumulative load effect on a wood member, and if strength of the member can be predicted, then the structural reliability of the member can be predicted. For example, when dead loads plus live loads are plotted together a load effect curve such as shown on the bottom portions of the two curves shown in Figure 11 might be obtained. Here, live loads from occupants and natural hazards such as wind, snow, or earthquake, result in the spikes rising from the baseline. The baseline itself varies as the sustained live loads, such as furniture, etc.,

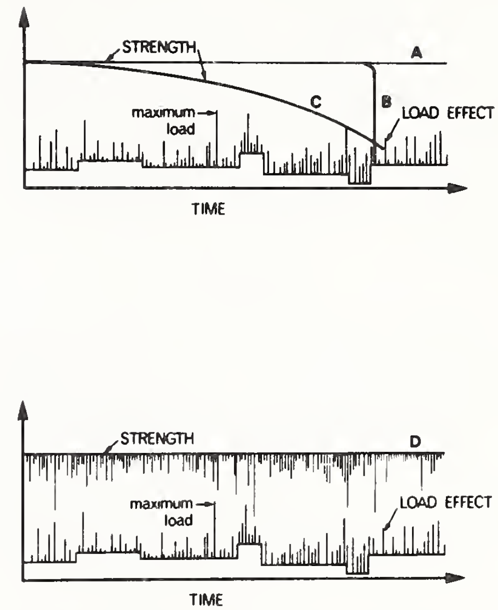

Figure 11. Variation in both load and strength that may occur over time (lower curve). If strength deteriorates with time (upper curve) failure occurs when load exceeds strength (Sexsmith, Fig. 3 in symposium paper).

vary. Curve A of Figure 11 represents constant strength, while curve B represents a sudden loss in strength, such as might be caused by a fire. Failure occurs when strength curve B intersects the load curve beneath it. For many adverse environments, wood strength gradually decreases with time, shown in curve C. If the loss in strength continues until load exceeds strength, the member fails. Long-term chemical degradation, decay, weathering or long-term heating could cause this type of strength loss. In some cases, strength losses may be only temporary, as shown by curve D.

This could represent the "immediate" temperature response as was shown in Figure 1, or a brief moisture content increase. An example of strength change due to a sudden moisture content increase for a specimen already under load was shown in Figure 5, in which case failure occurred for loads of 0.4 or more of the short-term strength. In this situation, as in Figure 4, a creep effect is also present, so a purely straight baseline as in curve D of Figure 11 would not be assumed.

Since adverse environmental conditions for wood in use lead to strength variability with time, it is important to design structures for which the probability of exceeding the limit state is sufficiently small for the particular

structure or structural component in question. A serviceability as well as a failure limit state must be considered. These two limit states imply assigning a cost benefit calculation to design decisions, with the designer determining an optimum safety level in which cost and safety levels or serviceability, or the probability of exceeding the limit states, are evaluated. This procedure involves sociological decisions to be made, since the consequence of failure must be given a cost factor. There remains much room for research.

STRUCTURAL COMPONENT TESTING

Testing of structural components is necessary to determine the service life, or period of time that properties of the component meet or exceed minimum acceptable values. Service life varies depending on the component, so that easily repaired or replaced components, such as paints and coatings, do not have to last as long as structural members that must function for at least the intended service life of the structure with little or no maintenance.

It must be recognized that materials have finite service lives because they gradually undergo deterioration due to chemical, physical or mechanical changes until their performance level becomes less than acceptable. Testing service life involves measuring a property before and after aging takes place. Once a known rate of degradation can be determined and baselines for original property levels and minimum acceptable levels are determined, then a service life can be predicted. The essential problem is to substitute a short-term test for new or innovative materials where long-term testing using typical use environments would take too many years to be practical.

Suitable short-term tests and correlations between short-term and long-term testing programs continue to be developed and must continue to be developed whenever an innovative approach to an existing problem or product is suggested. This process can be shortened if mechanisms of degradation can be determined so as to quantify degradation factors. Interactions between important variables must be measured. For new use conditions, insight into appropriate interactions is obviously necessary. Degradation mechanisms induced by short-term tests must be identical to mechanisms present in long-term in-service degradation. If appropriate degradation factors can be quantified, the state of the art of service life prediction will be advanced. If the degradation factors listed in Table 4 are fully understood, then use of wood in new use situations could be predicted and adequate design or treatment precautions could be taken before the wood is placed in use.

Table 4. Degradation factors affecting the service life of building components and materials

---

I. WEATHERING FACTORS

- A. Radiation
  - Solar
  - Nuclear
  - Thermal
- B. Temperature
  - Elevated
  - Depressed
  - Cyclic
- C. Water
  - Solid (e.g., snow, ice)
  - Liquid (e.g., rain, condensation, standing water)
  - Vapor (e.g., high relative humidity)
- D. Normal Air Constituents
  - Oxygen and ozone
  - Carbon dioxide
- E. Air Contaminants
  - Gases (e.g., oxides of nitrogen and sulfur)
  - Mists (e.g., aerosols, salt, acids, and alkalies dissolved in water)
  - Particulates (e.g., sand, dust, dirt)
- F. Freeze-thaw
- G. Wind

II. BIOLOGICAL FACTORS

- A. Microorganisms
- B. Fungi
- C. Bacteria

III. STRESS FACTORS

- A. Stress, Sustained
- B. Stress, Periodic
  - Physical action of water, as rain, hail, sleet and snow
  - Physical action of wind
  - Combination of physical action of water and wind
  - Movement due to other factors, such as settlement or vehicles

IV. INCOMPATIBILITY FACTORS

A. Chemical

B. Physical

V. USE FACTORS

A. Design of System

B. Installation and Maintenance Procedures

C. Normal Wear and Tear

D. Abuse by the User

Source: Masters, L. W. Predictive service life testing of structural and building components

Service life testing, using short-term tests that can be directly related to long-term in-service performance would speed qualifications of wood treatments or wood products for adverse environmental applications. Techniques for proceeding with carefully specified short-term testing programs have been developed and can be applied to many of the research needs on effects of the environment on design properties of lumber.

RESIDUAL STRENGTH EVALUATION

Research conducted on use of wood in adverse environments is intended to avoid deterioration of the wood or to evaluate response of the wood to the particular adverse environment. However, as the number of old wood structures increases with time, and as pressures for space utilization in existing structures increases as opposed to construction of new structures, there are increasing efforts to determine the best methods to evaluate residual strength of existing structures that are intended for rehabilitation, conversion to an alternate use, or that have suffered obvious deterioration and must be evaluated to determine how strength has been changed and what repairs are necessary. The increasing concern over product liability may also justify evaluation of performance of wood-based products.

During a structural evaluation, results of the design, construction, maintenance and repair functions that must be followed by responsible building owners becomes apparent. Too often, inattention to these functions does not become obvious until many years later, at which time costly remedial measures become necessary.

A structural evaluation must precede any repair actions. The extent of the evaluation depends on the type of structure, method of construction, past history and intended future use of the structure, and immediate goals of the owner--whether for repair of known defects, a structural alteration, a need to meet modern building codes, or change in occupancy. If past history of the structure can be determined accurately, then many of the strength-reducing factors mentioned in the first part of this review can be used to assess the present condition of wood structural members. That is, prolonged heating at high temperatures, obvious presence of water for substantial periods of time, prolonged loading at very high stress ratios, contact with chemicals, evidence of fastener corrosion or rusting iron, or accidental overloads known to have occurred could each have reduced future load-carrying capacity.

Numerous tools are available to help with the structural analysis, and there is considerable room to allow for ingenuity in planning methods to obtain necessary information, such as ways to perform dead load testing without disturbing occupancy. Methods to rapidly and accurately measure residual strength are needed. There are a few problems to overcome. The method must be nondestructive. When establishing handbook data, destructive testing is appropriate, but in testing existing structures either no destructive tests are possible or only a very limited number of structural members can be removed for destructive testing. Dead load testing to measure deflection and recovery is often utilized effectively. When testing for deterioration, microscopic analysis of borings or nondestructive testing methods can be used to advantage, X-rays can reveal density differences due to decay or presence of old repairs or stiffeners, and infrared scanning can be used to locate studs in walls through which heat is flowing. Stress waves can be used to determine elasticity or can be adapted to map locations of decay so the extent of needed repairs can be charted (Fig. 12).

Moisture distribution in existing structures must always receive attention. Presence of old machinery that used water or caused condensation, poorly maintained or detailed roofs, windows, and doors, restricted ventilation of attics or crawl spaces, condensation dripping from cold pipes or leaks in plumbing seem obvious signs of potential moisture-related problems. An increasing difficulty will be to evaluate insulated walls, roofs and floors where inadequate vapor barriers were used, especially when insulation was

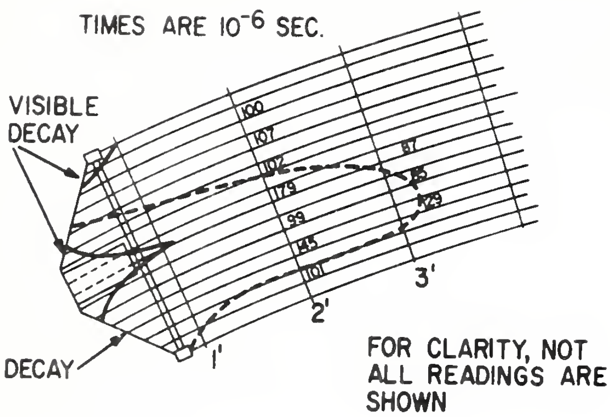

Figure 12. Stress wave times measured in situ at the base of a decayed glulam arch that was exposed to the weather (Courtesy of R. J. Hoyle, Jr.).

added to save energy costs in cold climates. If the data in Figure 13, showing moisture content on the inner surface of plywood sheathing of insulated walls with winter exposure in Madison, WI, is considered, the gradual decay that could develop over a period of years can be judged by noting the number of days each heating season that high moisture levels can occur in walls with no vapor barrier. Each structure will behave differently due to construction, type of occupancy and climatic differences. However, the recent retroinsulation activity due to high energy costs has set the stage for many instances of degradation

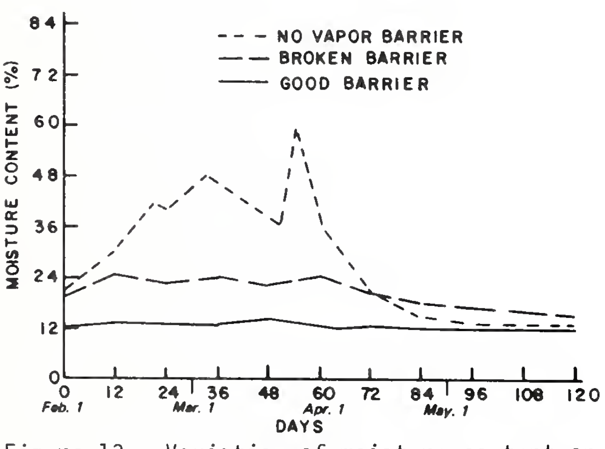

Figure 13. Variation of moisture content on inner (warm) surface of plywood sheathing for test walls of heated house in Madison, WI, with various types of vapor barriers over 3 inches of fiberglass insulation in stud wall cavity (adapted from Duff, 1968 by Bodig).

in improperly insulated structures.

Following a structural evaluation, various types of repairs or reinforcement might be necessary to either restore or increase load-carrying capacity or stiffness of beams, connectors, etc. Numerous techniques have been outlined but are not appropriate for the purpose of this review.

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APPENDIX I

Information for this review was taken from the following state-of-art invited review papers prepared for the symposium, Structural Use of Wood in Adverse Environments. Proceedings of the symposium will be published in 1981.

Barrett, J. D. Effects of loading time on design

Beall, F. C. Effect of temperature on the structural uses of wood and wood products

Bodig, J. Moisture effects on structural use of wood

Corotis, R. B. Design of timber structures for natural hazards

DeGroot, R. C. and G. R. Esenther. Microbiological and entomological stresses on the structural use of wood.

Feist, W. C. Weathering of wood in structural use

Lanius, R. M., Jr. Evaluating residual strength and repair of structures

Masters, L. W. Predictive service life testing of structural and building components

Mottet, A. L. Adverse effects of processing environments on working stresses

Richards, B. R. Marine borers

Sexsmith, R. G. Limit states design methods

Suddarth, S. K. Structural environments

Thompson, W. S. Adverse environments and related design considerations--chemical effects

RESEARCH NEEDS ON BIOLOGICAL AND CHEMICAL FACTORS--

REPORT OF THE TASK GROUP

A. Effects of chemical environment on the strength of wood and its fasteners.

This research area covers a broad spectrum of research needs that range from the effect on wood of wood preservatives and fire-retardants to the interactions of wood in a chemical environment.

1. Strength reductions associated with kiln drying of wood treated with salt-type preservatives and fire-retardants.

Temperatures up to 240° F are being employed to an increasing extent to dry CCA-treated dimension lumber. It is suspected that this practice is causing major strength reductions in stock thus dried. The proposed study is intended to provide the data base whereby the extent of damage can be assessed and acceptable drying schedules developed.

2. Degradation of fasteners by fire-retardant treated lumber.

There are reports of rapid corrosion and ultimate failure of metal fasteners employed with fire-retardant treated lumber. The purpose of this study is to determine the scope of the problem, ascertain which formulations are the main contributors to the problem, and develop methods of protecting metal connectors used with such wood.

3. Fundamental investigation of the effect of chemicals on wood.

The existing body of information on the effects of chemicals and chemical atmospheres on wood properties is inadequate for the increasingly hazardous environments in which wood is used. This study is intended to focus on the response of various wood properties to a wide range of chemicals and thus expand the data base in this important area.

4. Strength reductions in large timbers associated with steam conditioning periods in excess of those permitted by relevant standards.

Poles, piling, and sawn timbers are frequently reconditioned and retreated if they fail to meet applicable quality criteria after the initial treatment. The effect on mechanical properties of this additional exposure to steam has not been fully documented, but is believed to be significant based on the limited data available. A study of this problem is needed to determine the effect on the various strength properties of wood of steaming periods from 1 to 15 hours greater than those permitted by AWPA Standards.

5. Effect of preservative and fire-retardant chemicals on afterglow and hygroscopicity of wood.

Wood treated with chromium-containing salt formulations and exposed to fire are subject to a phenomenon in which the wood continues to be consumed by a slow combustion process after the fire has been extinguished. Likewise, wood treated with the retentions of fire-retardant formulations required to be efficacious tends to remain damp as a result of adsorption of moisture from the atmosphere. Methods of preventing or lessening the importance of these phenomena are the objectives of this study.

B. Fundamental studies of the mechanism of biodeterioration in a natural environment.

Much of the available data base on biodeterioration of wood is anchored to laboratory investigations in which the attack on wood occurs under essential ideal conditions and in the absence of competing organisms. Information thus generated frequently is found to be fallacious when applied under field conditions. What is proposed here is a broadly based study of deterioration of treated and untreated wood in a natural setting that will focus on such matters as the natural progression of organisms on (in) decaying wood; the progress of decay and how it is influenced by environmental factors; and the interaction of other organisms as they affect the progress of decay (antagonistic or synergistic).

C. Nondestructive assessment of existing strength of wood subjected to biological, chemical, or thermal exposure.

Quantification of the influence of environmental factors on structure members requires a nondestructive method of determining the residual strength of members exposed to a hazardous environment. In the case of incipient decay, it is crucial that the area affected be ascertained so that appropriate adjustments in member properties can be made. The proposed study is open-ended in that any promising method will be evaluated. Mechanical, microscopic, electrical, and chemical (i.e., degree of polymerization) methods that are based on existing technology will be evaluated first.

D. Maintenance requirements of wood structures.

Proper maintenance is an essential ingredient in the satisfactory performance of wood structures. Lack of judicious maintenance procedures is responsible for the premature failure of items ranging from utility poles to homes. The focal points of this study will be to identify maintenance requirements of a broad range of structure types; investigate the effectiveness of various maintenance programs; document the efficacy of preventive and remedial preservative treatments; and publish literature designed to inform the general public of maintenance programs appropriate for homes, boats, and other domestic structures.

E. Identification of hazardous environments.

Data are either lacking or not available in usable form on those forces of nature which individually or collectively act to shorten the useful life of wood. A compilation of existing data or generation of new, by region in the U.S. and Canada, is needed on climatic and biotic factors which act on wood, along with protective or remedial treatments that can be applied.

F. Studies of biodeterioration and weathering damage to light-frame structures.

The protective envelope which comprises the wall, floor, and roof systems of frame structures creates an environment favorable to insect and fungal activity and deterioration by weathering. A comprehensive study is proposed of design, site, and use factors which contribute to damage by these biotic and weathering factors that will identify problem areas, develop basic information on the mechanism of damage development, and seek practical solutions.

Dave Barrett
Rodney DeGroot
Wallace Eslyn
William Galligan
Robert Meyer
Roger Rowell
Stan Suddarth
Warren Thompson, Chairman
Jerry Winandy

EFFECT OF PRESERVATIVE TREATMENTS AND EXPOSURE CONDITIONS ON THE MECHANICAL PROPERTIES AND PERFORMANCE OF WOOD[1]

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ABSTRACT

Significant losses in strength of wood associated with decay occur well in advance of detectable changes in such physical properties as weight and color. Thus, the occurrence of even incipient decay in untreated load-bearing members usually dictates that such members be replaced. Preservative treatments provide protection against biological deterioration, but both the processing operations and certain salt-type preservatives have the potential of reducing the mechanical properties of wood. Strength losses induced by decay and by preservative treatments are discussed.

INTRODUCTION

The satisfactory performance of wood in many of its structural and non-structural applications is contingent upon either maintaining a moisture content below that necessary for decay or treating the wood with a preservative. The first solution is a practical one; it is widely employed in frame construction, a market which consumes over 50 percent of the annual U. S. production of lumber, plywood, and reconstituted wood products. That this method can be used successfully is attested to by the hundreds of antebellum homes in the South, a region with a relatively harsh biotic environment. However, reports of insect and decay damage to frame structures in excess of $2 billion annually and recent survey data which show that a dismally high percentage of the homes in some sections of the country harbor active insect or decay activity provide convincing evidence that problems exist with this method of protecting wood in service (Levi, 1978; DeGroot and Dickerhoof, 1975).

Pressure treatment of structural members with preservatives is mandatory where service conditions are conducive to biological deterioration. If it is assumed that the treatment applied is of such quality as to preclude damage from insects and decay, strength losses associated with the preservative treatment itself assume importance. It has been shown that conditioning wood preparatory to treatment and, in the case of inorganic salt formulations, the preservatives themselves can have a deleterious effect on the mechanical properties of wood.

The purpose of this presentation is to review briefly the effects of decay and wood-preserving processing treatments on the strength properties of wood, identify areas where additional research is needed, and discuss the concept of quantifying the influence of decay and treatment effects on structural size members.

EFFECT OF DECAY ON MECHANICAL PROPERTIES

Review of Data Base

Wood subjected to decay undergoes changes in its physical, mechanical, and

[1]Paper presented at the Workshop of Research Needs on Effect of the Environment on Design Properties of Lumber, Forest Products Laboratory, Madison, Wisconsin, May 28-30, 1980.

chemical properties not unlike those induced by a strong oxidizing agent or mineral acid. It loses weight, sustains changes in color, volume, and hygroscopicity and may, depending upon the invading organism, suffer major reductions in strength and chemical composition. The chemical changes incurred by decaying wood, and the attendant reductions in mechanical properties, are caused by a system of enzymes capable of catalyzing the rapid disassociation of cellulose molecules and, in the case of white-rot fungi, the breakdown of lignin. These chemical changes apparently take place well in advance of invading hyphae and are often responsible for dramatic strength reductions which have been shown to occur before changes in such physical properties as weight can be detected.

How rapidly strength reductions occur in decaying wood varies with the species and type of fungus, species and moisture content of wood, and such environmental factors as temperature and humidity. That such reductions occur have been recognized since biblical times and, in recent years, have been studied extensively (Hartley, 1958; Wilcox, 1978). Some of these studies have had as their objective to find a measure of decay more sensitive than the traditional weight-loss method. A brief summary of the results reported by selected investigators follows:

Crushing Strength

Several studies have shown the relationship between this strength property and infection of the living tree by *Fomes pini*, *Polyporus schweinitzii*, and other fungi (Schrenk, 1900; Abbott, 1915; Scheffer *et al*., 1941). Variability in results caused by the difficulty of obtaining sets of uniformly infected specimens for testing and the inability to relate observed crushing strength values to other measures of decay, such as weight loss and specific gravity, complicate attempts to relate levels of deterioration to losses in crushing strength.

More definitive data are provided by studies in which laboratory-infected specimens were used. Thus, for example, Atwell (1947) found that crushing strength was reduced 6 percent in specimens that sustained an average weight loss of 1 percent after exposure to *F. pini*. A reduction of 37 percent in this property corresponded to a weight loss of 4 percent. Scheffer (1936) working with *Polyporus versicolor* on sweetgum reported that reductions in crushing strength were 1.5 times as great as the corresponding weight reductions. Both the brown rot *Poria vaporaria* and the white rot *Polyporus hirsutus* were found by Asano and Fujii (1953) to cause losses in crushing strength in the early stages of decay of beech that exceeded weight losses by a factor of three.

That reductions in crushing strength occur in advance of and more rapidly than weight loss was demonstrated by Toole (1971) who tested specimens of several species in radial compression following predetermined periods of exposure to cultures of both brown-rot and white-rot fungi. Results for southern pine exposed to *Poria placenta* are given in Table 1.

Table 1.--Effect of decay by *Poria placenta* on strength reduction in southern pine specimens tested in radial compression[1]

Incubation Time (days)	Weight Loss	MOE	Stress @PL	Stress @ 5% Comp.
	--- % Reduction ---			
1	0.0	+2.4	+0.6	0.2
2	0.0	6.3	2.5	0.5
3	0.1	8.1	0.5	2.7
4	0.0	1.8	+2.3	0.3
5	0.1	1.5	7.9	3.0
6	0.5	1.5	4.7	5.6
7	0.9	8.3	11.8	11.6
8	1.8	16.7	13.6	16.9
9	2.1	7.6	18.9	17.8
10	2.9	31.0	28.4	23.8
14	11.6	62.5	71.5	70.4
21	19.2	79.9	83.1	83.0
28	31.8	83.2	83.3	85.0

[1]Adapted from Toole (1971).

Reductions in MOE, stress at the PL, and stress at 5 percent compression were recorded prior to any detectable reduction in weight. Results of correlation analyses indicated that stress at 5 percent compression was a more sensitive and less variable measure of decay than either MOE or stress at the PL. The relationship between this value and weight loss for southern pine and sweetgum exposed to brown-rot fungi is shown in Figure 1.

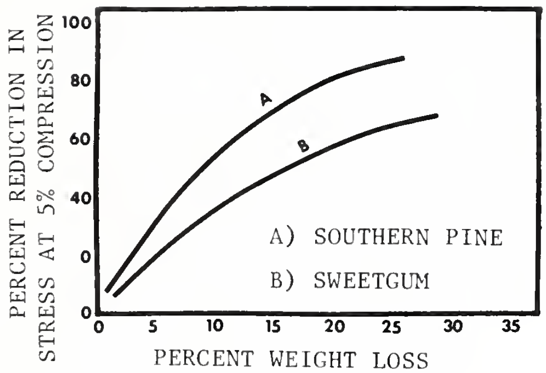

Figure 1. - Relationships between stress at 5 percent compression strain to weight loss caused by three brown-rot fungi decaying southern pine and sweetgum.

Tensile Strength

Only limited data appear to have been published relating progressive changes in tensile strength to levels of decay. Hopkins and Caldwell (1944) measured this strength property of thin (0.01 inch) specimens of birch following burial in unsterilized soil. Untreated specimens lost 95 percent of their strength in 10 days and all of it in 14 days. Treated specimens sustained strength losses of between 0 and 76 percent, depending upon treatment efficacy.

Brown (1963), who also utilized tensile strength to assess efficacy of preservative treatment, cited versatility, sensitivity to levels of deterioration, and the short incubation time required to obtain definitive results as advantages of this method compared to the traditional weight-loss method. Data on weight and strength loss for specimens of ponderosa pine veneer treated with tributyltin oxide and exposed to Gloeophyllum trabeum for 10 days are shown in Table 2 for three specimen thicknesses. The relatively large reduction in tensile strength associated with modest weight losses shown in Table 2 lends credence to Brown's conclusion that the sensitivity of this strength property to decay could be utilized in the evaluation of wood preservatives. In this regard, Pettifor and Findlay (1946) utilized tensile tests to demonstrate that--contrary to popular belief--certain staining fungi cause measurable reductions in this strength property.

Table 2.--Effect of decay by G. trabeum on the tensile strength of ponderosa pine veneer treated with tributyltin oxide[1]

Treatment Retention (pcf)	Weight Loss (%) 1/4"	1/8"	1/16"	Strength Loss (%) 1/4"	1/8"	1/16"
6.7×10^{-4}	0	1.36	4.71	20.2	48.1	61.1
13.4×10^{-4}	0	1.05	2.82	23.1	40.2	43.5
20.1×10^{-4}	0	1.08	2.33	18.1	45.3	45.2
26.8×10^{-4}	0	0.40	2.10	7.1	15.1	41.4

[1]Source: Brown (1963).

Bending Strength

That the strength of wood in static bending is affected by decay well in advance of weight loss has been recognized since the work of Longyear (1926) who correlated loss in bending strength with weight loss of specimens following their burial for various periods of time in damp soil. Although his study was crude by modern standards, the results that he reported established the relationship between decay and strength that has been confirmed by numerous subsequent studies.

Strength loss in bending commences at an early stage and continues at a more-or-less uniform rate until it approaches 100 percent. This relationship is illustrated in Figure 2, as reported by Cartwright and Findlay (1958). The figure shows that Sitka spruce exposed to P. placenta sustained a reduction in maximum fiber stress of more than 40 percent before a reduction in weight of the specimen was recorded.

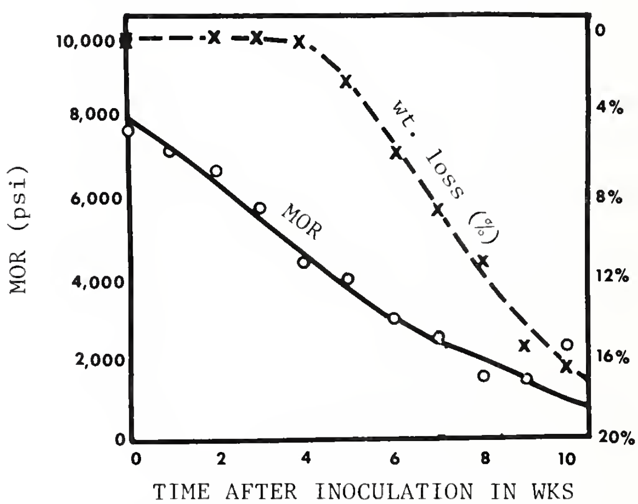

Figure 2. Relationships between weight loss and strength of Sitka spruce exposed to P. placenta.

Scheffer (1936) studied the progressive effects of Poly. versicolor on sweetgum sapwood and reported an effect on modulus of rupture (MOR) very similar to that found by Cartwright and Findlay. This strength property was rapidly reduced at first. However, after this initial rapid drop, the rate of reduction remained uniform for the remainder of the study. The reductions in specific gravity of the test specimens occurred at a consistently slower rate than MOR. Thus, a reduction in specific gravity of about 25 percent corresponded to a reduction in MOR of about 35 percent. Although more variable than MOR, losses in both modulus of elasticity and fiber stress at the proportional limit also occurred at proportionately faster rates than losses in specific gravity.

In a similar study, Mulholland (1954) tested Sitka spruce specimens in bending following exposure for 14 days to cultures of P. placenta. A separate set of specimens were removed from culture, conditioned, and tested at two-day intervals, along with a matched set of controls. Reductions in MOR relative to that of the controls were recorded after an exposure period of four days and became progressively larger until termination of the study after 14 days. The reduction in MOR on the 14th day was about 13 percent. No change in weight was recorded until the 10th day. Changes in MOE and fiber stress at the proportional limit during the study were small, irregular, and non-significant.

Shock Resistance

Shock resistance, as measured by toughness and by work in static bending, is the mechanical property of wood most sensitive to decay. Thus, it has been found that while the deleterious effects of white rot on other mechanical properties of wood are generally less than those caused by brown-rot fungi, the effect of white rot on shock resistance is large and immediate. This effect is illustrated by the work of Cartwright, et al. (1936) who investigated the reductions in the mechanical properties of oak following exposure to Poly. hispidus (Figure 3). While the bending strength was only slightly reduced in the early stages of decay, toughness was reduced by 20 percent after two weeks and 90 percent after 12 weeks. The corresponding reductions for MOR, MOE, and crushing strength after 12 weeks were 16, 5, and 10 percent, respectively.

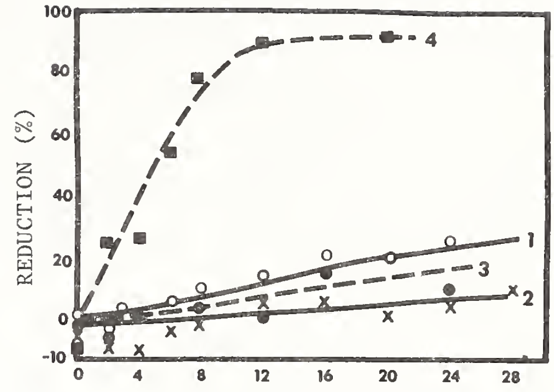

Figure 3. Relationship between reduction in toughness, bending strength, crushing strength, and modulus of elasticity of ash and time of exposure to attack by P. hispidus.

Similar results have been reported by other investigators. Scheffer, et al. (1941) found that both the brown-rot fungus Poly. schweinitzii in Douglas-fir and Sitka spruce and the white-rot fungus F. pini in Sitka spruce have a greater effect on work in static bending than on other strength properties. Likewise, this author (1936) reported that work to maximum load for sweetgum specimens exposed to Poly. versicolor was affected more by decay than MOR and other measures of bending strength. Then, too, Mulholland's work (1954) showed a 37 percent reduction in work to maximum load for Sitka spruce after an exposure period of 14 days to cultures of P. placenta. The corresponding reduction in MOR was 13 percent.

The value of toughness as an index is illustrated best by the works of Pechmann and Schaile (1950) and Richards (1954), which are summarized in Tables 3 and 4, respectively. Pechmann and Schaile measured changes in weight and toughness of specimens at ten-day intervals following inoculation. Their data show reductions in toughness in the range of 15 to 37 percent for weight losses of 1 percent or less, the exact value varying with wood-fungus combination. After an incubation period of 40 days, the reduction in toughness for all combinations of woods and brown-rot fungi ranged between 72 and 92 percent.

Table 3.--Percentage losses in weight and toughness in softwood and hardwood specimens exposed to decay fungi[1]

Days incubated	Coniophora puteana		Poria vaporaria				Merulius lacrymans		Polyporus versicolor	
			Sapwood	Heartwood	Sapwood	Heartwood				
	Wt. (%)	Tough. (%)	Weight (%)		Toughness (%)		Wt. (%)	Tough. (%)	Wt. (%)	Tough. (%)
					Spruce					
10	+0.9	15	+0.3	+0.3	15	15	+0.5	12	...	...
20	2.3	55	2.2	2.2	43	43	1.5	55	...	...
30	5.4	62	7.0	7.0	72	72	3.2	62	...	...
40	13.3	82	12.0	12.0	86	86	6.0	72	...	...
50	...	...	17.7	17.7	91	91	8.0	78	...	...
60	...	...	...	...	...	...	...	...	...	...
					Pine					
10	0.9	37	+0.6	.....	7	...	...	...	...	...
20	4.2	59	2.7	+0.2	45	18	...	...	...	...
30	5.4	59	6.0	2.2	62	50	...	...	...	...
40	8.5	76	11.4	.....	87	...	...	...	...	...
50	16.4	79	16.6	8.6	93	71	...	...	...	...
					Beech					
10	+1.0	27	+0.6	+0.6	6	6	+0.4	8	0.5	23
20	2.5	61	.4	.4	32	32	1.3	31	2.1	26
30	6.5	84	3.8	3.8	71	71	2.6	56	7.7	45
40	8.0	85	8.1	8.1	89	89	9.2	92	10.9	60
50	12.0	91	12.2	12.2	94	94	15.7	96	13.9	66
60	...	...	...	...	...	...	...	...	...	...

[1]Source: Pechmann and Schaile (1950).

Poly. versicolor, the only white-rot fungi represented in the study, caused a reduction of 60 percent in beech during this period. The corresponding weight losses ranged from 6.0 to 13.3 percent.

Richards' data are particularly useful because his experimental design permits a comparison of variations of weight losses and toughness losses. This comparison, as presented by Hartley (1958), is shown in Table 4. As were true in Pechmann and Schaile's study, large reductions in toughness accompanied early infection of the specimens and equalled 84 to 90 percent after an exposure period of 14 weeks. The reduction in weight during this same period was about 20 percent for all fungi except Polyporus abietinus, for which the weight loss was about 12 percent.

A comparison of the ratio of the coefficient of variation for toughness loss to that for weight loss gives an average value for all fungi and woods studied by Richards of 0.53. This value indicates that toughness is a less variable index of decay than weight loss. Hartley (1958) analyzed strength- and weight-loss data from various sources and concluded that toughness alone among strength properties is less variable than weight loss,

Table 4.--Comparison of variations of weight losses and of toughness losses[1]

Wood and fungus	Weeks in decay jars	Mean losses of-- Weight (%)	Toughness (%)	Coefficient of variation (Standard error as percent of mean loss) Weight	Toughness	Ratio of toughness to wt.
Sap pine	0					
Poria placenta	2	1.1	55	40	19	0.47
(brown rot)	4	4.3	76	29	10	.35
	6	6.5	72	28	22	.79
	8	11.2	77	26	20	.77
	14	21.8	90	12.5	6.9	.55
Geometric mean						.56
Polyporus abietinus	2	0.2	17	57	75	1.31
(white-pocket rot)	4	1.4	61	25	8	.32
	6	3.5	70	17	11	.66
	8	5.2	76	16	6.8	.42
	14	11.8	86	4.4	5.1	1.16
Geometric mean						.67
Sap gum	0					
Gloeophyllum trabeum	2	2.8	36	43	42	.98
(brown rot)	4	4.0	36	32	43	1.33
	6	9.4	56	36	27	.74
	8	12.9	77	26	13	.52
	14	20.0	84	18	7.5	.42
Geometric mean						.73
Polyporus versicolor	2	4.4	72	31	11.1	.35
(white rot)	4	5.5	75	19	6.8	.36
	6	8.3	85	27	4.9	.19
	8	10.6	86	16	4.8	.30
	14	21.4	87	15	4.5	.30
Geometric mean						.29
Geometric mean of all fungi						.53

[1]Source: Hartley (1958) based on data supplied by Richards (1954).

and, hence, has potential as an alternative index of decay. However, Amburgey and Behr (1979) reported that toughness of treated specimens decayed by G. trabeum was not strongly correlated with weight loss. They attributed this result to non-uniform decay of the relatively long test specimens employed.

Application of Laboratory Data

Although the data base relating strength losses to deterioration of wood by decay fungi is anchored almost entirely to test results for small specimens, the weight of evidence indicates that by the time decay progresses to the point that it can be detected visually in untreated members, significant strength losses will have occurred. Shock resistance is the mechanical property most rapidly affected by decay, followed in approximate order of susceptibility by bending strength, compressive strength, and hardness. Fungi which cause brown rot rapidly reduce all strength properties. They are by all standards the more important of the two groups of fungi economically, since

the white rots are not commonly found associated with decay of softwood structural members.

If it is assumed, as stated above, that serious strength reductions occur before decay can be detected, the question of quantifying the effect of decay on untreated structural members becomes academic. The problem becomes one instead of identifying pieces containing decay and replacing them with sound members. This remedy presupposes that the cross section of the member is uniformly infected. There may be no alternative to this assumption in certain critical structural applications of wood; that is, where failure would present an imminent hazard to human life.

In less critical applications involving treated wood, it is a common practice to determine the proportion of the cross section affected by decay and make a determination either to replace or leave in service the decayed member. The distinction between treated and untreated wood is important here, since it is possible in a treated member for the decay to be localized by a retention of preservative in adjacent wood adequate to prevent decay. This situation is a common one in utility poles. For example, for a pole containing center rot, the sound-shell thickness is determined and an appropriate reduction made in measured pole circumference to compensate for the defect. If the pole meets specifications after making this adjustment, it is left in service; otherwise, it is replaced with a sound pole of the proper size.

As an example of the reasoning used to determine whether a particular pole can safely be left in line, consider an actual case of a Class 6, 35' long pole 8.28" in diameter. The sound shell thickness is 8.28-3.52/2 = 2.38". Standard practice requires that the measured circumference of the pole be reduced by 2 inches. It would be left in service only if a smaller pole, in terms of circumference, meets applicable standards. In other words, if a Class 6 pole is specified for the service conditions in question and reducing the circumference from 28 inches to 26 inches dictates a reclassification to a Class 7, the pole would be replaced.

In fact, the actual reduction in strength of this particular pole is probably insignificant. The percentage of the original strength retained by the decayed pole can be calculated as follows:

$$\frac{I_{8.28} - I_{3.52}}{I_{8.28}} \times 100 = 96.7$$

$$\text{Where } I = \pi D^4/64$$

In other words, the pole has retained approximately 97 percent of its original strength after having sustained a loss to decay of about 18 percent of its cross sectional area. Calculations of residual strength for structural members in which decay areas assume other conformations--for example, an external decay pocket--would be more difficult, as discussed further below.

One problem in estimating the residual strength of a decayed structural member is in ascertaining that the "sound" wood has not in fact sustained damage from decay in the incipient stage. This would seldom be a safe assumption for untreated wood, and there have been no studies which verify that the apparently sound wood adjacent to decayed areas in treated members is in fact free of decay. On the contrary, the evidence available for poles indicates that once decay begins, it continues to involve successively larger proportions of the cross section unless a remedial treatment is applied. Research is needed to ascertain the progress of decay in infected, treated timbers and whether or not apparently sound wood adjacent to decayed areas contains incipient decay.

A second problem is one of estimating reliably the effect on strength of infected areas that might assume any one of several conformations within a structural member. Empirical determinations, such as the example above, can be made for such defects as hollow heart, enclosed decay pockets, and external decay pockets. However, these determinations, which often are little more than rules of thumb, are not anchored to test results of full-size members. Clearly, research is needed to provide a data base with which to relate decay damage in structural members to strength losses.

On a more basic level, a reliable non-destructive method is needed for field identification of wood containing incipient decay. As observed above, weight loss is the standard method of assessing the effects of decay. However,

it is based on weight changes, which ordinarily could not be determined for structural members, and is, in any event, unreliable, since significant strength losses can precede weight changes in the early stages of decay.

Changes in volume, shape, and hygroscopicity are known to occur in decaying wood, but all of these are normally associated with levels of decay that can be detected visually. In addition to being unsuited for field application, they are not consistent indexes of decay. For example, practically no change in shape or volume accompanies decay of wood by white-rot fungi. Then, too, the equilibrium moisture content of wood has been reported both to decrease (Findlay, 1956; Scheffer, 1936) and increase (Mulholland, 1954) with the onset of decay.

The use of deflection in bending under a non-damaging load has been proposed by Mateus (1954) as a means of detecting decay. While perhaps applicable to uniformly decayed laboratory specimens, it is impractical for use with structural members.

Richards (1952) reported on a method of identifying decay in wood that, with further development, may offer some promise. He found that certain decay fungi increase the conductivity of wood and thus cause a difference between estimates of moisture content based on dielectric constant and those based on conductivity. A difference of 3 percent in the two readings was found by him to be indicative of decay. He was able to detect decay accurately in 33 percent of his specimens that had sustained weight losses of 1 to 2 percent, in 83 percent of those that had weight losses of 3 to 4 percent, and in all specimens with weight losses greater than 4 percent.

An even more serious data gap exists in assessing damage caused by insects. Although it is assumed, for example, that termites are capable of causing extensive strength reductions in wood, there apparently are no published data on either the magnitude of the loss or the rate at which it occurs. Information on strength losses caused by insects seems to be limited to two studies, one published (Williams and Barnes, 1979a, 1979b) and one unpublished (Thompson, 1963), both of which dealt with powderpost beetles (*Xyletinus peltatus*).

Table 5.--Mean strength properties of southern pine floor joist samples at two densities of *X. peltatus* exit holes/0.0929 m^2 of wood surface[1]

	Beetle exit-hole density class	
Characterictic	0	31+
No. samples	579	254
Mean no. beetle holes	0	70.3
Sp gr	0.556	0.557
% latewood	40.2	39.9
MOR (MPa)	58	38.6
MOE (MPa)	8884	6932
Wpl (J/m^3)	30.48	20.32
Wml (J/m^3)	157.72	86.88
% undamaged MOR	99.5	66.2
% undamaged MOE	97.4	76

[1]Source: Willams and Barnes (1979a).

The results of the study conducted by Williams and Barnes are summarized in Table 5. Simple counts of beetle exit holes, along with radiography, were used as visual indices of damage. Damaged wood from buildings more than 30 years old was not significantly weaker than undamaged wood from the same building. However, there was a clear reduction in all strength properties with increasing number of exit holes. MOR, MOE, and work to maximum load values for specimens containing an average of 70 exit holes were smaller than those for undamaged specimens by 34, 22, and 45 percent, respectively.

EFFECT OF PRESERVATIVE TREATMENTS ON MECHANICAL PROPERTIES

Some of the treatments to which wood is subjected during preservative treatments have an effect on its mechanical properties. Important in this regard are incising and conditioning, both of which are frequently used on stock preparatory to preservative treatment. Treatments with certain preservatives are themselves reported to have an effect on the strength properties of wood. Most of these effects are negative; that is, the wood sustains a reduction in strength as a result of the processing operation.

However, the beneficial effects associated with these operations--principally improvement in the quality of preservative treatments and a commensurate extension of service life--are generally considered to be more than worth the associated negative effects.

Incising

A review of the effect of incising led Perrin (1978) to conclude that this process probably has a negligible effect on the strength properties of large items such as poles and crossties. However, for timbers having a cross section smaller than that for crossties the results were mixed, as indicated for Douglas-fir in Table 6, which was adapted from Perrin's report (1978).

More definitive results on the effect of incising than those shown in Table 6 were reported by Schrader (1945) following an examination of the effects of the process on the strength of Douglas-fir laminated beams. Beams 8" x 18" in cross section fabricated from 1-inch lumber and beams 8" x 16" prepared from 2-inch lumber sustained reductions in bending strength of from 10 to 20 percent as a result of 5/8-inch-deep incisions applied at a rate of 65 per square foot. Dimension lumber has also suffered strength losses from incising. Thus, for example, 2" x 2" samples of Norway spruce were reported to have lost 16 and 13 percent of their MOR and MOE, respectively, following incising to a depth of 1/4-inch with 860 incisions per square foot (Banks, 1973). Likewise, redwood dimension sized for use in cooling towers lost from 7 to 28 percent of its bending strength during studies of incising that involved incision depths and frequencies of 1/4-inch and 860 per square foot, respectively (Kass, 1975).

Conditioning

Steaming

That steam conditioning at the pressures and for the duration permitted under existing standards may cause significant strength losses in treated products is no longer a matter of serious debate. Numerous reports have dealt with this subject (Buckman and Reese, 1938; Davis and Thompson, 1964; MacLean, 1951; Wood, Erickson and Dohr, 1960). They show conclusively that there is a range of temperatures--short of that required to cause outright destruction--within which wood undergoes chemical degradation and sustains losses in strength to a degree dependent upon the duration and severity of exposure.

Much of the original work on the effect of steaming on the mechanical properties of wood was conducted by MacLean (1951, 1952, 1953). Following a study in which small specimens were steamed at temperatures of 250°F to 350°F for 8 to 32 hours, he concluded that shock resistance was the property most

Table 6.--The effect of incising on the strength of Douglas-fir timbers and ties[1]

Dimensions (inches)	No. of incisions per foot	Change in strength (%)				
		Bending			Compression	
		FSPL	MOR	MOE	CS par.	CS perp.
4 by 8	64	-8	-15	-4	-4	-7
4 by 8	64	-18	-15	-14	-17	-33
4 by 8	64	-4	-9	-4	-3	+3
4 by 8	64	+2	+11	-6	-5	-5
6 by 12	75	-2	0	-7		
6 by 12	75	-4	-7	-4		
7 by 8	75					-10
7 by 9	76					-8
7 by 9	76	+6	+4	0	+3	+6
7 by 10	90					+17

[1]Adapted from Perrin (1978).

seriously affected, followed in order by MOR, fiber stress at the PL, and MOE (MacLean, 1953). A similar order of effect was reported by Thompson (1969a) based on bending tests of Class 6, 30-foot southern pine poles and compression tests of 3-foot piling sections. Results of the latter work are summarized in Table 7. They show that shock resistance is the mechanical property affected most by steaming and MOE, the property affected least. The reduction sustained is a function of steaming duration, as shown in Table 8, and steaming temperature. Other studies show that reductions in strength during steaming occur concurrently with, and are caused by, changes in chemical composition, particularly the carbohydrate fraction (Thompson, 1969b).

Table 7.--Reduction in strength properties of southern pine associated with steam conditioning[1]

Strength property	Reduction (%)
Shock resistance (Toughness tests of small clear specimens)	30
Fiber stress at elastic limit (Static bending tests of 30-foot poles)	29
Modulus of rupture (Static bending tests of 30-foot poles)	27
Fiber stress at elastic limit (Compression tests of 3-foot piling sections)	21
Maximum crushing strength (Compression tests of 3-foot piling sections)	20
Modulus of elasticity (Static bending tests of 30-foot poles)	8
Modulus of elasticity (Compression tests of 3-foot piling sections)	9

[1] Source: Thompson (1969a, 1969b). Each value is based on 50 tests.

Table 8.--Effect of steaming on the crushing strength of southern pine piling sections[1]

Type Specimen	Steaming Period (hr.) 0	8	16
Treated piling section	3260	2163	2182
Untreated piling section	3307	2640	2824
%-treated/untreated	98.6	81.9	77.3
Treated clear specimen	3614	2640	2524
Untreated clear specimen	3524	3062	3162
%-treated/untreated	102.5	86.2	79.8

[1] Source: Thompson (1969). Each value is the average of 50 tests.

Boulton Drying

Conditioning of wood by the Boulton process has less deleterious effects on wood than steam conditioning because of the lower temperatures (180-210°F) that are used. As in the case of steaming, strength reductions caused by the process at a given temperature are determined by the duration of the conditioning process, by species, and by the size items involved.

Data compiled by Graham (1980) on the effect of three conditioning processes on the strength of Douglas-fir sawn products are of interest (Table 9). Reductions in MOR for timbers in the size range of 6" x 12" to 8" x 16" that were Boultonized at temperatures of 190° to 215°F ranged between 5 and 18 percent and averaged about 10 percent in tests conducted by Rawson (1927), McFarland (1961), Luxford and MacLean (1951), and Harkom and Rochester (1930). Reductions in MOR for 1-inch and 2-inch stock exposed to the same temperature averaged almost 12 percent; items in this size class that were kiln-dried or vapor-dried in the temperature range of 220° to 250°F sustained reductions in MOR of 18 to 21 percent.

Reductions in MOR caused by Boultonizing for 30-foot Douglas-fir and western larch poles were reported by Wood _et all_ (1960) to be of the same order of magnitude as those for sawn products (Table 10). Larch was the species most seriously affected, showing a decrease in MOR and MOE of 17 and 20 percent, respectively.

Table 9.--Effect of conditioning on the modulus of rupture of Douglas-fir[1]

Author	Specimen size (inches)	140-170°F	190-215°F	220-230°F	250°F	Heat source
		(% reduction based on controls)				
Eddy and Graham (1955)	2 x 2		-9	-18	-21	Organic vapors
		-4				Kiln drying
Graham (1980)	1 x 1			-16		Organic vapors
		-7	-16			Kiln drying
Harkom and Rochester (1930)	6 x 12		-13			Boulton drying
Kozlik (1968)	2 x 6	-1	-10	-21		Kiln drying
Luxford and MacLean (1951)	4 x 8		-4			Boulton drying
	8 x 16		-9			Boulton drying
			-12			Boulton drying
			-7			Boulton drying
			-8			Boulton drying
MacFarland (1961)	7 x 16		-18			Boulton drying
Rawson (1927)	6 x 12		-5			Boulton drying
			-7			Boulton drying

[1]Source: Graham (1980).

Table 10.--Effect of conditioning method on the strength of 30-foot poles[1]

Species	Conditioning method	Modulus of rupture	Modulus of elasticity
		(% of unseasoned controls)	
Longleaf and slash pines	Steam & vacuum[2]	-23	-12
Shortleaf and loblolly pines	Steam & vacuum	-34	-16
Douglas-fir	Boulton drying[3]	- 7	- 4
Western larch	Boulton drying	-17	-20
Lodgepole pine	Air drying	+ 4	+ 3
Western redcedar	Air drying	- 4	- 1

[1]Source: Wood, Erickson, and Dohr (1960).

[2]Steaming conditioning was conducted at 259°F for 8.5 to 13.5 hours.

[3]Boulton drying was conducted at 195 to 210°F for 16 to 30 hours and a vacuum of 17 to 25 inches of mercury.

However, these values were smaller than the reductions sustained by steam conditioned southern pine, which ranged from 23 to 34 percent for MOR and 12 to 16 percent for MOE.

Vapor Drying

The effect of this conditioning process on wood strength is somewhat greater than that of Boulton drying because of the higher temperatures employed. Eddy and Graham (1955) found reductions in MOR of 9, 18, and 21 percent following vapor drying of 2" x 2" Douglas-fir at 190, 225, and 250°F, respectively. Reductions in work to maximum load were, in order, 17, 36, and 49 percent.

EFFECT OF PRESERVATIVES

The pH of treating solutions of some water-borne preservative formulations must be maintained within certain limits to prevent precipitation of the heavy-metal salts of which they are composed. Some of the solutions may be quite acid. Thus, for example, chromated copper arsenate (CCA) solutions may have a pH as low as 1.6, and the acidity of acid copper chromate (ACC) solutions may range from pH 2.0 to 3.9. By contrast, ammoniacal copper arsenate (ACA) is quite alkaline in reaction, since solutions of this preservative must contain a weight of ammonia equal to 1.5 to 2.0 times the weight of the copper oxide; copper oxide comprises 47.7 percent of the dry weight of the formulation.

The effect of the pH of the treating solution and, indeed, the effect of the preservative salts themselves on wood properties have not been clearly defined. Thompson (1964) investigated the effect of CCA, ACA, and ACC on the toughness of sweetgum, yellow-poplar, and blackgum veneer for retention levels of 1 to 4 pounds per cubic foot. Toughness of sweetgum and yellow-poplar was not significantly affected by the treatments. However, he reported that blackgum sustained important reductions in this property, the toughness values varying with retention. Evidence of embrittlement was observed in specimens of all species containing retentions greater than about 1.0 pound per cubic foot. Subsequent analyses of the toughness specimens revealed that the chemical composition of the wood, particularly carbohydrate content, was altered by high retentions of all three preservatives.

Additional evidence that high retentions of salt-type preservatives may reduce the shock-resistant properties of timbers was supplied by Wood (1980). Specimens cut from southern pine pole sections treated to a retention of 2.5 pounds pcf were found to have significantly lower values of toughness and work to maximum load than untreated control specimens (Table 11). Although not significant statistically, there was a trend toward lower bending strength among specimens treated to this retention (Table 12). An effect of retention values lower than 2.5 pcf on strength properties was not evident from Wood's data. This latter result is consistent with other data by Kelso (1978) which show no deleterious effects of CCA retentions on the bending strength of wood at retentions of less than 1.0 pound per cubic foot (Table 13).

Table 11.--Effect of high retention of CCA-type preservative on shock resistance of southern pine wood[1]

Retention (pcf)	Toughness (in. lb.)	WML (in.lb./in.^{3})
0	236	14.4
1.0	223	15.6
1.2	219	14.6
2.5	165	10.7

[1]Source: Wood et al. (1980). Each value is the average of 32 tests.

Table 12.--Effect of high retention of CCA-type preservatives on bending and compressive strength of southern pine pole sections[1]

Retention (pcf)	MOR (psi)	MOE (psiX10^{-6})	CS (psi)
0	16,350	2.21	3355
1.0	16,450	2.18	3485
1.2	16,350	2.06	3530
2.5	15,500	2.08	4005

[1]Source: Wood et al. (1980). Each value is the average of 32 tests.

Table 13.--Effect of steaming on the strength in bending of southern pine pole sections containing 0.6 pcf of CCA preservative[1]

Steaming Temp. (°F)	Duration (hr.)	MOR (psi)	MOE (psi)
0	0	1.56×10^4	1.78×10^6
210	3	1.59×10^4	1.80×10^6
210	6	1.58×10^4	1.86×10^6
240	3	1.60×10^4	1.93×10^6
240	6	1.56×10^4	1.86×10^6

[1]Source: Kelso (1977). Each value is the average of 31 to 60 tests.

How reduced shock resistance revealed by studies of small specimens translates to full-size structural members is unknown. Marine piling is the only item for which retentions of CCA-type preservatives in excess of 2.0 pcf are employed. Definitive data on the effect of such treatments on piling are not available, but it is generally conceded within the industry that piling treated with CCA tend to break during driving more frequently than those treated with creosote.

Strength reductions associated with treatments with oil-type or oil-borne preservatives are attributed to conditioning and not to the preservatives themselves. For example, it has been shown that the crushing strength of 3-foot piling sections cut from kiln-dried stock and treated with creosote was essentially the same as that for untreated, matched controls (Thompson, 1968). Reductions in this strength property occurred only among specimens that were steam conditioned preparatory to treatment (Table 8).

Reductions in both shear strength and wood failure have been reported for treated compared to untreated laminated wood. These reductions have been attributed to changes in the surface properties of wood brought about by the preservative chemicals (Thompson, 1962; Bergin, 1962; Selbo, 1959).

The relationship between strength and such processing variables as conditioning cycle and preservative retention is fairly easy to quantify. While most of the data to which this relationship is anchored are based on tests of small laboratory specimens, there exists a significant body of data derived from tests of full-size members. These data have already been used to make adjustments in allowable loadings for piling. The opportunity exists for making appropriate adjustments for other structural items as well.

Clearly, gaps that exist in the current data base must be filled before such adjustments can be routinely applied. One such information gap that is assuming increasing importance is the effect of kiln drying on the strength properties of salt-treated dimension lumber, poles, and timbers. There is reason to believe--in the absence of supporting data--that significant reductions in strength are being caused by drying practices at some wood preserving plants. It is not uncommon for salt-treated dimension to be dried at 240°F. Results of tests of a small number of sections cut from salt-treated poles accidentally dried under high-temperature conditions support this concern. Research is needed to determine the scope of this problem and to develop kiln schedules that will keep strength losses of treated wood at an acceptable level.

Another problem that must be addressed before knowledge of the effect of conditioning and drying on the performance of treated structural members can be put to much practical use is determining the pre- and post-treatment processing to which such members have been exposed. Under current industry practice, there is no way to ascertain with certainty the conditioning schedule employed preparatory to treatment or, in the case of salt-treated stock, the drying schedule used following treatment. As indicated above, the duration of steaming has an important effect on the mechanical properties of wood. This fact assumes special significance in view of existing industry standards which permit retreatment of stock that fails to meet quality criteria regarding retention and penetration of preservative. Thus, non-conforming poles are frequently reconditioned and retreated. The loss in strength resulting from this practice is suspected as the causal factor in the failure of several apparently sound poles investigated by our laboratory.

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QUANTIFYING POTENTIALS FOR WOOD DECAY

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ABSTRACT

Available data do not permit precise definition of environmentally dependent biological hazards for wood used above ground, but the concept of regional quantification of biologic potentials is well established. Regional variation in potentials for decay in wood, above ground, is emphasized. The criteria which can be used to quantify those regional potentials need definition.

INTRODUCTION

In 1956, the Building Research Advisory Board (BRAB 1956) recommended that control measures for wood used in residential construction be balanced with potentials for biological hazard. In 1980, with increasing concerns about product performance, escalating materials costs, and enhanced public environmental awareness, this recommendation has added significance. The assessment of potentials for biological impact must account for regional and site-specific variations in environment, construction detailing, and relative probabilities for biological damage to occur within specific components or structural members. Differences between organisms in rate and mode of attack must also be considered.

The U.S. Minimum Property Standards (USHUD 1973) currently address regional variations in anticipated windloads, seismic risk, and attack by subterranean termites, but do not address quantitative regional variations in potential for decay in wood used above ground. In this paper, the concept of regional variation in potentials for decay in wood above ground is emphasized. Additional discussion, of variations within and around structures that influence potentials and rates of attack, is offered to illustrate the interrelationships between environment, biological degradation, and structural performance of wood members.

In aboveground, exterior wood construction, the frequency with which minimum requirements for growth of decay fungi are met is influenced by climate, exposure at a given location to prevailing elements (storms, sun, etc.), and by construction practices. The concept that much decay can be prevented through designs and construction practices that keep wood dry is well known, but even with proper design, some exterior construction is exposed to the elements.

The definition of regional zones of potential biological hazard can be exceedingly important for specifying appropriate material requirements and protective measures. Climate-dependent gradations in hazard for decay in wood used above ground have been theoretically estimated (Scheffer 1971), but have not been independently field verified. Quantitative climate-dependent, geographic variations in decay hazard must be determined if building regulations and standards are to progress to a proficiency level whereby required protective measures relate to regional variations in potential biological hazard.

In the Southeastern continental United States, the contour lines representing wood decay hazard (Scheffer 1971), climatic regions in terms of moisture-temperature index of plant growth (Visher 1954), and percentage of annual leaf production which can be decomposed within 12 months (Meentemeyer 1974), are similar. The similarity of these contours, representing different phenomena, supports the concept of regional quantification of biologic potentials.

Scheffer's decay hazard index for interior cities seems particularly influenced by annual rainfalls. Comparing data from field surveys (table 1) in Mobile County, Ala. (DeGroot and Dickerhoof 1975), and in Raleigh, N.C.

Table 1.--Incidence of decay problems in houses surveyed in Mobile County, Alabama,[1] and in Raleigh, North Carolina[2]

House age	Raleigh, N.C. - 66[3] Percent with decay	Raleigh, N.C. - 66[3] 95 percent confidence interval[4]	House age	Mobile County, Ala. - 99[3] Percent with decay	Mobile County, Ala. - 99[3] 95 percent confidence interval[5]
Yr	Pct	Pct	Yr	Pct	Pct
0 - 5	3	0 - 6	0 - 3	15	3 - 27
6 - 10	6	2 - 10	4 - 13	24	17 - 31
11 - 20	19	14 - 24	14 - 23	34	25 - 43
20+	19	13 - 25	24 - 33	25	11 - 37

[1]DeGroot and Dickerhoof, 1975.

[2]Peterson and Levi, 1975.

[3]Scheffer Index Value.

[4]Computed from published data.

[5]Computed from data collected by DeGroot and Dickerhoof, 1975.

(Peterson and Levi 1975), it seems that the Scheffer Index is a better indication of decay incidence in older homes than in newer houses.

Available data do not permit more precise definition of environmentally related performance criteria and protection requirements of wood used above ground. A better understanding of the relationships between components of climate and the progress of naturally established decay is needed to enable better definition of regional levels of protection needed in wood used above ground.

Attempts to quantify the structural impact of biodeterioration must encompass variation within individual structures as well as between regions. For example, decay is often a problem at the unions of wood members where rain seepage is enhanced and opportunities for quick drying are reduced. Decay in a member exposed to a continuous source of moisture may show a uniform decay gradient from point of initiation, in to sound wood, or it may have a markedly nonuniform pattern of attack.

Modern control strategies for subterranean termites in the United States stress prevention of attack. However, when termites gain entry to a house, they may spread quickly from foundation to attic, causing varying degrees of damage within their area of infestation.

The location of wood decay fungi and wood destroying beetles in subfloor components, over crawl spaces that lack vapor barriers, is influenced by the moisture content of the wood. Thus, decay problems due to winter condensation, will be predominately on the north side of crawl spaces.

To prescribe the impact of biodeterioration within a structure, it is necessary to know what magnitudes of structural weakening can be tolerated in various components without compromising the entire structure, and to identify which component or which combination of components will be the first to limit the structural performance of the composite. For example, how important is the core of an individual member in construction elements such as studs or sill plates? Future technological advancements may ultimately enable treatment of presently refractory species to increased depths, but not with complete penetration. Will it be possible to design and construct durable structures with individual members that may ultimately be hollowed out by a biodeteriorgen? Use of a fault tree analysis to quantify potential (probability and magnitude) biohazards may be a logical first step in developing specifications for the construction of durable, individual structures.

Brown-rot fungi predominate in above-ground, softwood construction (cf. DeGroot 1976). The rapidity with which strength properties are reduced by brown-rot fungi is so great that weight loss is an insensitive indicator of strength reduction in brown rotted wood (Kennedy 1958). Substantial reductions in strength can occur before brown-rot type of decay can be detected with a microscope (cf. Wilcox 1978). Hence, improved techniques for estimating strength properties of incipient decay (less than 10 pct weight loss) are needed to improve capabilities for risk assessment with partially decayed timbers.

In summation, building regulations currently address some of the onsite potentials for biological attack. If duration of performance in differing environments is to be addressed with greater precision, variation in potentials for decay will need to be quantified. The criteria, which can be used to quantify those regional potentials, need definition, and as tolerances for biological damage to wood members decrease with increased usage of engineering design, greater precision is also needed for predicting potential of biological damage in individual construction elements.

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STRENGTH PROPERTIES OF BLUE-STAINED WOOD FROM BEETLE-KILLED SOUTHERN PINE TIMBER[1]

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ABSTRACT

Heavily blue-stained clear wood specimens sawn from beetle-killed southern pine were found to be weaker in toughness, flexure and compression than those from healthy trees. The longer the time after foliage fade of the infested trees, the greater the strength loss. When grading rules were applied conservatively, in-grade strength properties of full-size beams of the infested material were comparable to those from healthy trees.

INTRODUCTION

During the early and mid 1970's, the southern pine beetle, Dendroctonus frontalis Zimm., caused one of the largest insect infestations in southern forests. In 1973 alone, over 170 million board feet of sawtimber were marketed from beetle-devastated stands of southern pine (USDA 1975). Much of the lumber produced from beetle-killed trees have been found heavily stained as a number of staincausing micro-organisms infest the wood in the dead trees.

It has been reported by Davidson (1955) and by Hines et al. (1965) that most species of bark beetle attacking conifers are carriers of wood-staining fungi. After a beetle attack, the sapwood develops a blueish-gray stain and then the stain-causing fungi penetrate rapidly to the heartwood in Engelmann spruce (Hines et al. 1965). Craighead (1928), Leach et al. (1934), Rumbold (1931, 1936) and Bramble et al. (1940) provided conclusive information for the belief that bark beetles are carriers of wood staining fungi and thus directly inoculate the trees they attack. In optimum growth conditions the daily penetration rate for such blue-staining fungi is 0.5 mm tangentially, 1.0 mm radially and 4.5 mm longitudinally, according to Lindgren (1942).

Certain properties of wood are altered after infestation by blue-staining fungi. Chapman and Scheffer (1940) reported the following properties reduced in intensely blue-stained pine sapwood: specific gravity 1-2%, hardness 2-10%, bending and crushing 1-5%, and toughness 25-30%. In several other studies on strength properties of blue-stained pine, only toughness has been reported to be affected to any significant extent. Sinclair et al. (1978, 1979b) found significant reductions in toughness of heavily stained southern pine wood taken from beetle-killed trees. Although the specimens tested were free of defects with the exception of sap stain, which is not currently considered

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a degrade by grading rules, toughness generally decreased with increasing time after the death of the trees. Most of the loss in toughness occurred during the first year after foliage fade. Henningson (1967) theorized that early reduction in toughness might be the result of the splitting of the lignin-carbohydrate bond by the micro-organisms involved.

Strength properties other than toughness have also been reported to be affected after blue stain sets in the dead trees. Sinclair et al. (1979c) reported mean reductions of 19 and 12 percent in modulus of rupture and modulus of elasticity, respectively, in trees dead for 12 months. Maximum crushing strength was less severly affected. These results indicate that blue-stained southern pine lumber from beetle-killed trees may become of questionable quality not only in terms of toughness but also in static loading environments.

From the above studies it is not clear whether the changes in wood properties are a direct result of the blue-stain fungi or perhaps other organisms such as wood-destroying fungi cause the degradation. In studies on beetle-infested western conifers Nelson (1950) found that wood-staining is often associated by not only the stain-causing microorganisms but also by wood-destroying fungi. Lindgren (1953) and Barron (1971) reported fungal degradation following development of blue-stain in southern pine pulpwood and beetle-killed trees, respectively. Ifju et al. (1979) showed that such degradation in trees occurring during the first two years after foliage fade affect the quality of kraft pulp made from wood of those trees. Although pulp yield was not changed due to deterioration of the wood in the dead trees, tensile strength and tearing resistance of paper made from the pulp was gradually reduced over a two-year period. These results indicate that there may be severe degradation of the cell wall material in the dead trees involved.

The microbial activity in dead trees is affected by the moisture content of the wood, temperature, and a number of other environmental factors. Scheffer (1971) developed an index of the climatic potential for the decay of wood based on rainfall and temperature. According to Scheffer's rating, the geographic distribution of southern pine stands coincides with some of the areas of greatest hazard for wood decay on the North American continent. Garren (1939) related other factors, such as specific gravity of wood, to the rate of decay in dead southern pine sapwood.

Many investigators have reported that decaying dead trees may quickly become unsuitable for high quality solid wood products. Sinclair and Ifju (1979a) and Sinclair et al. (1977) found significantly lower lumber yield both on the volume and grade basis from dead southern pine trees when they were left on the stump for 12 to 20 months following foliage fade. All these results indicate that wood in dead trees showing blue stain also deteriorate with time to the point where its structural application may not be advisable. However, blue-stain, often the only visible mark on the lumber, is not considered degrade by the grading rules for structural material.

The objectives of this study were to determine the extent of strength reduction in blue-stained wood from beetle-killed southern pine trees and to relate the reduction to the time after foliage fade of the dead trees. It was also the purpose of this study to relate strength changes of small clear specimens due to wood deterioration to the behavior of full-size structural lumber sawn from beetlekilled trees.

MATERIALS AND METHODS

Small Clear Specimens

Representative bark beetle-killed plots of loblolly pine (Pinus taeda L.) and shortleaf pine (Pinus echinata Mill.) with known dates of foliage fade were located during the summer and fall of 1975. These plots were in the Piedmont and the Coastal Plain of Virginia in Lunenburg, Nottaway, and Charlotte counties and in the city of Suffolk. Since these two species are commonly marketed under a single name - southern yellow pine - and have quite similar properties (ASTM 1970), Koch 1972), both

were considered as belonging to one population in this study. Harvested sample trees were selected randomly from those dead trees that had reasonably straight boles, and logs were taken up to a minimum 7-inch top diameter. Trees were harvested at periods of roughly 2 months, 12 months, and 20 months following foliage fade. As dead trees were harvested, healthy control trees were also cut from the perimeter of the infested area. Approximately twice as many dead trees were harvested at each plot as control trees.

All sample trees were processed into lumber at one of three local sawmills each having similar equipment. Random pieces of lumber were selected to determine the applicability of current visual lumber grading techniques to dimension (8/4) lumber from beetle-killed southern pine. All sample pieces of lumber were graded by quality supervisors of the Southern Pine Inspection Bureau (SPIB). All 2 by 4's were graded as structural light framing, while 2 by 6's and wider stock were graded as structural joists and planks. (SPIB 1970)

SPIB grading rules severely limit decay in dimension grades of lumber but do allow sap stain (SPIB 1970). Because actual decay is usually easy to detect and is excluded according to current grading practices, no samples in which decay was readily evident were selected. Incipient decay and heavy sap stain, however, are not easily distinguished even by expert graders; therefore, no distinction between sap stain and incipient decay was made in the selection process. Since it is well known that the juvenile wood near the pith of southern pine has different strength properties than mature wood (Pearson, et al. 1971), samples from near the pith of the trees were also avoided.

Sample boards, one for each log, were selected from the graded dimension lumber on the green chain of the sawmill and air-dried. Small clear test specimens were machined from this lumber in accordance with ASTM standards (1977). Evidence of decay and juvenile wood was also avoided in the small specimen selection. By machining and testing small clear specimens from visually graded lumber it is possible to assess any deviations in basic strength values of small clear specimens from those values established for these species as a whole.

It should be noted that the sampling did not follow the ASTM standardized procedure (1977). However, it does provide realistic information on strength and stiffness of small clear specimens of commercially usable lumber. Property values determined from standardized sampling of whole trees were used in the derivation of design stresses for this lumber. Consequently, the data from this study, obtained from sections of lumber, should be comparable to those standarized values.

Three tests were conducted on wood obtained from the sample boards: static bending, compression parallel to the grain and toughness. All tests were conducted according to methods of ASTM D143-52 (1977) on material which had been conditioned to 12% moisture content (MC) prior to testing.

Two 1- by 1- by 16-inch static bending specimens were tested from each log. They were tested in center point loading with a span of 14 inches and a crosshead speed of 0.05 inch per minute. Two properties were calculated, modulus of rupture (MOR) and modulus of elasticity (MOE). Four 1- by 1- by 4-inch specimens were tested in compression parallel to the grain from each log using a crosshead speed of 0.012 inch per minute. Maximum crushing strength was calculated for each sample.

Four toughness specimens, each 2 cm x 2 cm x 28 cm, were tested from each log using a Forest Products Laboratory pendulum-type toughness machine. Two specimens were loaded on the tangential face nearest the pith and two were loaded on the radial face with toughness determined according to the standard procedure (ASTM 1977).

Small blocks were cut from each specimen near the zone of failure to determine specific gravity and moisture content. Specific gravity was calculated on an ovendry weight, green volume basis using a water displacement technique for measurement of green volume.

Full Size Lumber Specimens

During the late spring/early summer of 1977, a southern pine bark beetle infested forest of dead loblolly (*Pinus taeda* L.) and shortleaf pine (*Pinus echinata* Mill.) sawtimber was located near the vicinity of Lufkin, Texas. Infested trees were randomly selected approximately 12 months after foliage fade. Healthy control trees were selected from within and around the periphery of the infested areas. Control trees were chosen to approximate the diameter at breast height and the height distribution of the beetle infested trees. This practice met with some difficulty since control trees were hard to locate without straying too far from the infested stand, consequently approximately three times as many beetle-killed trees were harvested than control trees.

The trees were felled and bucked to standard even lengths, starting at 10 feet and progressing in increments of 2 feet up to 20 foot logs. Both ends of each log were marked to distinguish control logs from those obtained from beetle-killed trees, and to separate butt logs from upper logs, before the log was skidded and loaded.

A sawmill equipped with a circular headsaw and a gang rip saw converted the logs to lumber. The sawyer was instructed to maximize 2 inch dimension lumber with special emphasis on yielding 2 x 6 stock.

Each piece of lumber was marked according to log position in the tree and whether it came from a control or beetle killed tree. Lumber was then end-trimmed at the Texas Forest Products Laboratory to 8-foot lengths. Control boards were treated with a water-borne Wolman salt solution to retard the spread of blue stain. All lumber was then shipped to Blacksburg, Virginia and larger material resawn to 2 x 6 dimensions.

The lumber was air-dried in the laboratory for 5 months. Equilibrium moisture content for the beetle-killed lumber reached 9.9% in 3½ months while the sound material equilibrated at 10.8% and needed an additional month.

The rough, air-dry 2 x 6 lumber was then graded as structural joists and planks by an Southern Pine Inspection Bureau (SPIB) quality supervisor in accordance with SPIB grading rules (1977). Each board was meticulously scanned for limiting defects with particular attention focused on the identification of sapwood decay. While this level of scrutiny may be atypical of general grading practices in southern sawmills, it does adhere to the letter and intent of the grading rules.

Each board was then tested in third-point loading over a span of 7 feet with a constant crosshead speed of 0.1 inch/minute. Load-deflection curves were recorded for centerline deflection from which work to maximum load, modulus of rupture (MOR) and modulus of elasticity (MOE) were computed. The latter were adjusted for shear effects to give a true MOE using an estimated ratio of Young's longitudinal modulus/shear modulus (E/G) of 16.0.

Blocks containing the entire cross section from each board were cut near the zone of failure to determine the specific gravity (SG), calculated on a green volume, ovendry weight basis using a water displacement technique for volume determinations. Moisture content was assessed using an electric resistance meter.

RESULTS AND DISCUSSION

The experimental design for the small clear and the full size specimens does not allow prediction of the extent of degradation of wood in the whole tree following a beetle attack. In an earlier paper, it was reported that significant yield reductions occurred with time after death of the trees (Sinclair, et al. 1977). These yield reductions were due to the normal grade-sawing practices in which sawyers removed from the logs all apparently decayed material leaving relatively sound lumber for grading. Thus, the lumber cut from severely decayed logs was intended to be theoretically of the same quality as that sawed from healthy trees because the heavily decayed portions had been removed at the headrig.

In addition, each small clear specimen was carefully screened to insure that apparent degrade, such as ambrosia or other borer holes, was not present. However, sapstain was not a criterion for

rejection. Thus, comparisons with the small clear samples in this study are made between truly clear undamaged specimens which should all be long to the same population.

Comparisons between lumber from control and beetle-killed trees are also valid since both materials were subjected equally to the same set of grading criteria. However, no specific comparison can be made between the small clear specimen data and that from the full size lumber. This restriction is due to the geographical differences in temperature and moisture between Texas and Virginia. These differences may drastically alter the rates of decay between the areas.

Small Clear Specimens

Data collected were grouped on the basis of elapsed time between foliage fade and harvesting of the tree. Control specimens for bending and compression tests were also segregated according to their corresponding

plots so as to reduce the between plot variation and allow for meaningful comparison within any one group. The toughness control data was combined for analysis due to inadequate control sample sizes in some individual time groups. The groupings and tree characteristics are summarized in Table 1.

Bending

Table 2 shows the results of the flexure tests for specimens from both beetle-killed and healthy trees. In all cases, except Group 4, strength of the beetle-killed material was significantly lower than that of the corresponding control as determined by an unpaired t-test. However, in two cases, Groups 3 and 5, there was also significant difference between the SG values of the subgroups. Since it is well known that SG has a strong effect upon strength, it may be hypothesized that some of the difference in MOR may be due to the SG differential. However, it has also been shown that the effect of biological deterioration of wood upon strength may be significant prior to any observable loss in mass (Kennedy and Ifju 1962). Consequently, it may be appropriate to consider that strength reduction is due first to some modification of cell wall constituents by the fungi and secondly by a subsequent observable loss of mass. It is unknown whether the differences is SG were due to bio-deterioration or natural variability of wood in the test specimens.

To uniformly remove the effect of SG differences between dead and control samples, linear regressions were performed between MOR and SG for the control data within each group. Subsequently, the mean MOR values for the controls were adjusted with the use of the individual regressions so that comparisons could be made at equal SG levels. The coefficients of determination of all regressions of MOR on SG were in the range of 0.6 to 0.8 indicating a good level of correlation.

Table 3 indicates the ratio of mean values of data from specimens from infected trees to those of healthy controls. Ratios of data adjusted and unadjusted for specific gravity are shown.

Examination of the two ratios in Table 3 reveals that not all differences in MOR between dead and control trees could be removed by adjustment of values according to SG. The data indicate that a significant reduction in MOR occurred relatively soon after foliage fade with as much as 12 to 13 percent loss in strength adjusted for SG after 1 year. Total loss in MOR after two full warm seasons was approximately 19 percent. These losses cannot be fully attributed to decreases in SG and may indicate a significant strength loss without noticeable weight loss. The above results appear even more significant considering the biased sample material, which was free of all defects except sap stain and was cut from lumber meeting current grading criteria.

MOE, an indicator of material stiffness, was also determined from the bending data and was adjusted in a manner similar to that for MOR. Coefficients of determination of adjusting regressions ranged from 0.2 to 0.6. Tables 2 and 3 indicate that MOE was also affected by wood deterioration but not to the same degree as MOR. A total loss in stiffness of about 10 percent was only observed in material from trees standing for two full

Table 1.--Grouping of plots of beetle-killed southern pine according to length of time between foliage fade and sample collection.

Group	No. plots	Time between foliage fade and collection	Average tree characteristics DBH (inches)	Age (years)	Height (feet)
Control	8	--	12.7	62	73
1	1	2 Mo. (Fall-Fall[1])	10.8	63	65
2	3	12 Mo. (Smr.-Smr.)	12.2	71	70
3	3	12 Mo. (Wtr.-Wtr.)	13.9	53	74
4	1	≈20 Mo. (≈1-1/3 W.S.[2])	10.8	63	65
5	3	≈20 Mo. (≈2 W.S.)	12.8	48	70

[1]Season of foliage fade-season of collection.
[2]W.S. = warm season (April-October).

Table 2.--Summary of small clear specimen data from, and significance of difference between, static bending tests of beetle-killed and healthy southern pine at 12 percent MC.

Group	Time[2]	N Dead	N Control	Mean SG Dead	Mean SG Control	Sig.[1]	Mean MOR (psi) Dead	Mean MOR (psi) Control	Sig.[1]	Mean MOE (10 psi) Dead	Mean MOE (10 psi) Control	Sig.[1]
1	Fall-fall	48	21	0.465	0.49	NS	14,049	15,541	*	1,666	1,867	*
2	Smr.-smr.	99	24	0.45	0.46	NS	11,476	13,176	**	1,663	1,737	NS
3	Wtr.-wtr.	131	34	0.41	0.46	**	11,290	13,291	**	1,491	1,717	**
4	≈1-1/3 W.S.	53	33	0.45	0.44	NS	11,613	12,569	NS	1,773	1,700	NS
5	2 W.S.	106	81	0.42	0.44	*	10,136	12,435	**	1,398	1,570	**

[1] * Significant difference between means at the 0.05 level.
** Significant difference between means at the 0.01 level.
NS No significant difference between means.

[2]W.S. = Warm seasons.

Table 3.--Ratios of mean values of MOE, MOR, and ultimate compressive strength from beetle infested material to those from control samples adjusted and unadjusted for specific gravity.

	Ratio of Mean Values (Dead/Controls)					
	MOR		MOE		Ultimate Compressive Strength	
Group	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted
1	0.90	0.95	0.89	0.95	0.89	1.01
2	0.87	0.88	0.95	0.96	0.97	0.99
3	0.87	0.93	0.87	0.89	0.94	1.00
4	0.92	0.90	1.04	1.02	0.94	0.98
5	0.81	0.87	0.89	0.94	0.87	0.93

warm seasons of which a significant portion may be accounted for by differences in SG.

Because of the differential influence of the beetle infestation on MOR and MOE, the relationship between the two would be greatly different for beetle-killed as compared to control material.

Compression

SG and ultimate strength of wood in compression parallel to grain are tabulated, in Table 4 along with parameters for statistical comparison using the t-test. With the exception of one, all groups showed significant differences between healthy and infected specimens. However, as shown in Table 3, reduction indicated by mean value ratio was substantially less than that found for bending properties. If adjustments of mean values for SG differences are made, then relatively insignificant strength reductions are apparent. Although a 7 percent reduction (adjusted for SG) was found for specimens from trees standing for 20 months after foliage fade, it is difficult to attribute this difference solely to beetle infestation. Consequently, these data seem indicative of an insensitivity of crushing strength to stain and associated incipient decay.

Toughness

No attempt was made to adjust the toughness values to a common specific gravity because of a poor correlation between specific gravity and toughness in both the control specimens and those that exhibited stain and incipient decay.

Average moisture content at the time of testing for the various groups varied somewhat more than was considered optimal. However, it has been shown that toughness is relatively insensitive to small changes in moisture content within the hygroscopic range (Kollmann and Coté 1968).

The toughness test results are shown graphically in Figure 1 and are tabulated in Table 5. Figure 1 indicates that tangentially loaded specimens were tougher than the radially loaded specimens. Additionally, the butt log specimens were consistently tougher than those from the upper logs. This is likely due to the upper logs of southern pine having a generally lower specific gravity and to the observation that upper logs exhibit evidence of earlier decay than butt logs (Sinclair et al. 1977).

Table 5 is a summary of the average radial and tangential toughness values for butt and upper logs combined. The results indicated that the majority of the strength loss occurred in the first 12 months after foliage fade. This may be explained by noting that generally after 12 months, the main bole of the tree was sufficiently dried to partially inhibit decay.

A Sheffé multiple comparison, generally considered a conservative test, indicated that there was no significant difference between the means of groups 2-5 but that these groups were different from the controls and group 1. This may have significance in planning salvage operations of beetle-killed southern pine having recently experienced foliage fade.

Table 4.--Summary of small clear specimen data from, and significance of difference between, compression parallel to grain tests of beetle-killed and healthy southern pine at 12 percent MC.

Group	Time[2]	N Dean	N Control	Mean SG Dead	Mean SG Control	Sig.[1]	Mean ultimate stress (psi) Dead	Mean ultimate stress (psi) Control	Sig.[1]
1	Fall-fall	60	19	0.44	0.44	*	6,850	7,661	*
2	Smr.-smr.	267	57	0.45	0.46	NS	6,454	6,616	NS
3	Wtr.-wtr.	204	59	0.41	0.45	**	6,049	6,443	*
4	≈1-1/3 W.S.	129	72	0.44	0.46	NS	6,288	6,695	*
5	2 W.S.	240	174	0.41	0.43	**	5,479	6,243	**

[1] * Significant difference between means at the 0.05 level.
** Significant difference between means at the 0.01 level.
NS No significant difference between means.

[2] W.S. = warm seasons.

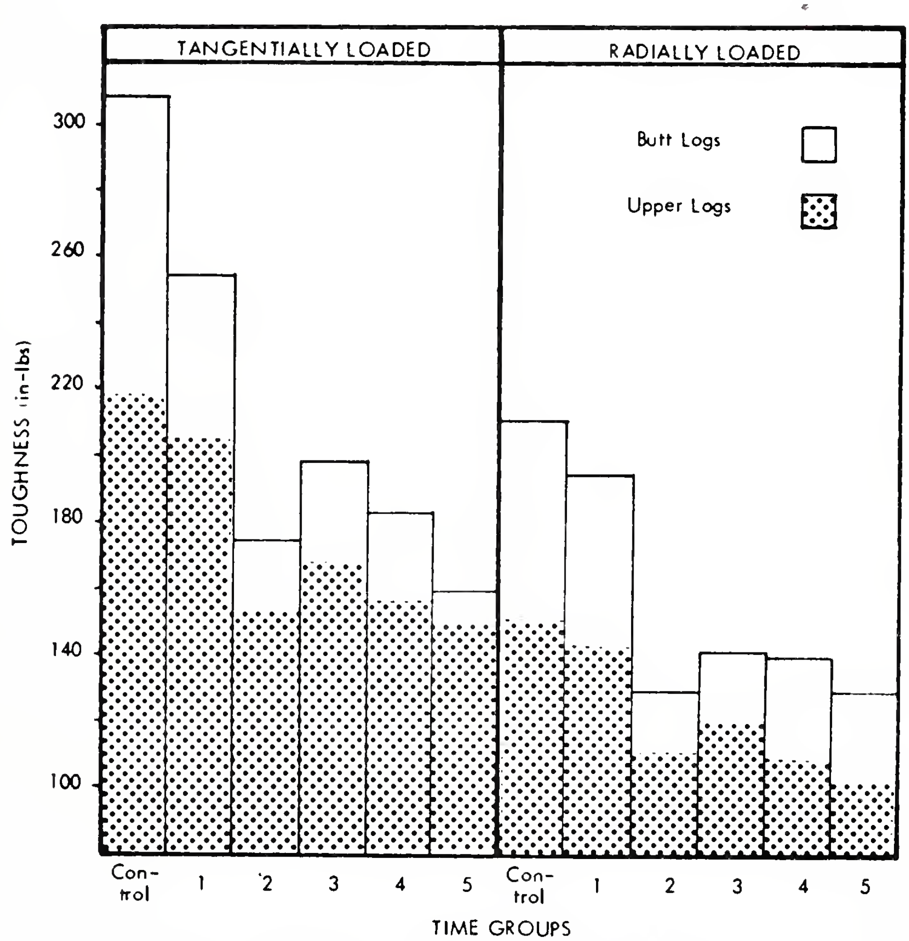

FIG. 1. Toughness of control and beetle-killed southern pine.

Table 5.--Summary of averaged radial and tangential toughness data with butt and upper log results combined.

Group	Time[1]	N	Moisture Content	SG	Toughness Mean	Std. dev.	Sheffé[2]
All Control		334	12.7	.45	224	65	A
1	Fall-fall	86	10.7	.45	211	70	A
2	Smr.-smr.	200	12.8	.44	144	49	B
3	Wtr.-wtr.	233	11.8	.41	156	48	B
4	≈1-1/3 W.S.	101	14.4	144	149	59	B
5	2 W.S.	210	12.1	.42	135	58	B

[1]W.S. = warm seasons.

[2]Means with the same letter are not significantly different at the 0.05 level using a Sheffé multiple comparison procedure.

Although the results showed little difference between the control and 2-month [1] groups, it should be noted that the 2-month [1] was on the stump for the months of October and November. If this group had been left on the stump during a two-month period more suitable for rapid decay, these results might have been altered. Preliminary results using a small number of matched specimens of beetle-killed southern pine indicated that losses in toughness may begin very soon after the death of the tree (Sinclair et al. 1978).

Full Size Lumber

Partial results of testing the 2 x 6 lumber in bending are presented Tables 6-8. Table 6 indicates the overall mean for all lumber sampled and the ratios of dead to control values. There appears to be a considerable difference between the beetle-killed and control material when all grades are aggregated. However, when the results are evaluated by grade, the differences as indicated by the ratios are less apparent (Table 7). This is reasonable, considering the low sample size within certain grades and that the visual grading scheme was designed to insure approximate equality within each grade. If there is an influence of blue stain on the full size material then its effect is not readily apparent in this limited sampling.

Nonparametric statistics were utilized in this study since the distribution of strength and stiffness were decidely skewed. Due to the small sample sizes of some of the distributions it was felt that parametric procedures would tend to be too sensitive to violations of distributional assumptions. In addition, distribution-free procedures became a logical choice because there existed prior knowledge that the sample distributions may not be normal.

Table 8 presents the results from an analysis using Wilcoxon's Rank Sum Test for equal medians in comparing the dead and control data. Wilcoxon's Test is used to test for the presence of a treatment effect that results in a shift in location such as mean or median. The hypothesis is that the two samples may be viewed as a single sample from one population. The alternative is that the treatment population has a different location than that of the cotrol. As can be seen from the table, the hypothesis can be rejected only where grades 1-3 are grouped together. It may also be rejected when all material is combined (Goehring, 1980).

These data tend to indicate that the current SPIB grading scheme of restricting sapwood decay does adequately segregate material within individual grades according to visual criteria. The results for the Economy grade (a non-structural classification) indicate that the grading may be overly conservative in that some higher quality material may be assigned to that class.

Table 6.--Results from static bending tests of all 2 x 6 lumber from beetle-killed and healthy control southern pine at 12% MC.

	N		Mean		Std. Dev.		Ratio
	Dead	Control	Dead	Control	Dead	Control	Dead/Control
MOR (psi)	210	78	5732	7252	2061	2613	.79
MOE (10^6psi)	210	78	1.48	1.52	.322	.359	.97
Specific Gravity	210	78	.454	.465	.053	.052	.98

Table 7.--Static bending results by grade for 2 x 6 lumber from beetle-killed and sound southern pine at 12 percent moisture content.

		No. of Observations		Estimated Mean		Stand. Dev.		Ratio
Property	Grade	Dead	Control	Dead	Control	Dead	Control	Dead/Control
MOR (psi)	1	4	46	8123	8305	1130	2177	.98
	2	33	14	6598	6507	1601	2548	1.01
	3	28	11	6298	5682	2084	1795	1.11
	Economy	145	7	5360	4291	2053	2852	1.25
	3 & Better	65	71	6563	7544	1823	2419	.87
MOE (10^6psi)	1	4	46	1.64	1.63	.140	.335	1.01
	2	33	14	1.62	1.47	.256	.328	1.10
	3	28	11	1.54	1.35	.318	.255	1.14
	Economy	145	7	1.43	1.54	.329	.386	1.25
	3 & Better	65	71	1.59	1.56	.280	.337	1.02

Table 8.--Results of Wilcoxon's Rank Sum Test for equal median values for flexural properties of 2 x 6 lumber from beetle-killed and sound southern pine.

Property	Grade	Dead	Control	Hodges-Lehman Estimated Median Differences. $\hat{\Delta}$	Wilcoxon's Probability Level, $\alpha(w)$
MOR (psi)	1	4	46	342	.3228
	2	33	14	- 27	.4801
	3	28	11	- 715	.1314
	Economy	145	7	-1203	.1292
	3 & Better	65	71	1041	.0052[1]
MOE (10^5psi)	1	4	46	- .41366	.4013
	2	33	14	- 1.68800	.0256[1]
	3	28	11	- 1.86840	.0375[1]
	Economy	145	7	- 2.77530	.0228[1]
	3 & Better	65	71	- .50850	.1562

[1]Reject the hypothesis that the median of the differences was zero.

As was pointed out earlier the grading procedures used may have been atypical of those found in southern pine mills. However, the results indicate that the written grading rules appear to be adequate for between-grade assignments.

A great deal of additional sampling would be required to assess potential within-grade differences at a selected percentile level of strength or stiffness. It is interesting to note in Table 7 that there was no apparent difference between the moduli of elasticity of the control and the infested samples. This is consistent with the results shown for the small clear specimens.

The lumber for full-size tests was harvested from trees approximately 12 months after foliage fade. The small clear specimen data indicate that this is the time frame in which most of the degredation occurs. Because of sampling limitations, it was not possible to assess material harvested at other time periods. This information would be particularly important for planning future salvage operations of beetle-infested forests and should be included in future research planning.

Because it is difficult to evaluate the extent of sapwood decay affecting the cross-section, severe restriction regarding its presence are inherent to the grading rules. These restrictions may cause usable lumber to be placed in a lower value class. Additional research oriented at a nondestructive evaluation of this material may be warranted.

SUMMARY AND CONCLUSIONS

Beetle-killed southern pine trees with known dates of foliage fade were harvested and processed into lumber. The sawyer took the usual course of removing all apparent decayed wood during the processing. This procedure resulted in lumber of theoretically equivalent quality to that sawn from the green control trees. Quality control supervisors graded the lumber according to SPIB rules, further assuring that the experimental material be classified into proper quality classes or grades. The only apparent difference between the beetle-killed and the control material was the consistent appearance of heavy blue stain and ambrosia beetle borings on the beetle-killed lumber, which are not

considered degrade in structural grades of southern pine. Small clear specimens from lumber obtained from infested and healthy control lumber were tested in bending, parallel-to-grain compression and toughness.

From the results of this study, it was found that significant reductions in MOR and MOE may be caused by incipient decay and associated sapstain as early as two months following foliage fade. These phenomena, which cannot be eliminated using limiting defects under current grading rules, contributed to a mean reduction of 19 percent in MOR and 11 percent in MOE after two full warm seasons subsequent to foliage fade. The elastic moduli were not affected to the same degree of severity as MOR. This caused a significant difference in the relationship between MOR and MOE of healthy and infected small clear specimens. The ultimate strength of small specimens in compression was relatively insensitive to the effect of incipient decay and associated sapstain. Toughness generally tended to decrease with increasing time after foliage fade with the majority of loss, a 30-40 percent decrease, occurring in the first warm season following death of the tree.

When full-size 2 x 6 lumber graded by SPIB quality control supervisors was tested in bending, no significant differences were found between the same grades of beetlekilled and control materials. This apparent contradiction between results on small clear specimens and those on full-size structural lumber was probably due to the unusually restrictive grading procedures applied. The graders participating in this study applied severe restrictions for "sapwood decay" when they were faced with heavily blue-stained lumber. However, such restrictions are not to the letter of the grading rules.

This study has provided evidence that heavily blue-stained southern pine lumber, such as that produced from beetle-killed trees, may be of lower strength than lumber clear of such stain. However, careful and conservative grading can segregate lumber into proper grades. Although no direct influence of bluestain on strength properties of lumber could be isolated in this study, such stain should be considered as a warning signal for the grader to apply grading rules conservatively.

RECOMMENDATIONS

Additional research should be directed towards more extensive sampling of full-size lumber from beetle-killed and other heavily blue-stained material in all grades. Sample sizes should be keyed towards assessing distributional influences since design values are usually based on some lower percentile rather than mean values.

Greater emphasis should be placed upon the use of nonparametric procedures for data analysis since distributional forms tend to be non-normal.

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IMPACT OF BIODETERIORATION ON

STRUCTURAL USE OF WOOD--RESEARCH NEEDS[1/]

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ABSTRACT

The interactions between wood, degrading organisms, and the environment are briefly discussed. Nine areas of research that impact upon design of wood structures are described and pertinent research studies falling within these areas are proposed.

INTRODUCTION

Biodeterioration of wood, its breakdown by micro-organisms and insects, impacts on all aspects of the structural use of wood including design, choice of building materials, and construction and maintenance practices. The potential severity of the interaction between the degrading organisms and their host varies widely, depending upon the surrounding in-use environment--particularly the availability of water to the wood.

While moisture availability is affected most by local climatic conditions, the entrapment and pickup of water by wood structures is governed by structural design, by wood species and condition, and by competency of construction and conscientiousness of maintenance of the structure.

Spores of decay fungi are ubiquitous so availability of inoculum is seldom a deciding factor in the infection of wood structures. However, insect hazard depends upon the presence of a source of insects, such as subterranean termites, carpenter ants, and powder post beetles, in the vicinity of the wood. Hence, choice of site for installation or construction impinges upon susceptibility of wood structures to insect infestation and subsequent degrade.

Where factors tend to favor biodeterioration, the option exists of using decay-resistant or preservative-treated wood for structural components. Exercise of this option may well dictate probability of initiation and rate of progress of fungal infection or insect infestation in the structure.

Use of treated wood does not inevitably result in protection from biodeteriorating agencies. Efficacy of treatment depends in part upon wood species involved. Certain woods like Douglas-fir, for example, are refractory and require incisement for satisfactory uptake of preservative solution. Even when adequately treated, wood--especially large timbers--may check deeply, exposing the untreated interior to attack by fungi and insects. In addition, treatment which may work well with softwoods may fail when applied to hardwoods, as in the case of CCA-treated poles and posts.

Where decay becomes established in structural members, problems arise when attempts are made to quantify extent of degrade and judge the capability of members to perform their load-bearing functions. Infected load-bearing members that still retain adequate strength can be considered for in-situ treatments.

As a consequence of this interaction between wood, degrading organisms, and environment, it is difficult to formulate reliable criteria for design of wood structures that takes biodeterioration into account. Pertinent information from scattered and fragmentary research studies on biodeterioration of wood

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need be amassed and evaluated in establishment of such criteria. Also, research needs necessary for attainment of this goal must be pursued. The objective here is to surface some of these research needs and provide information on direction for future studies to fill these research gaps.

RESEARCH NEEDS AND PROPOSALS

Nine areas of research in need of attention are:

1. Nondestructive determination of strength in deteriorating timbers in use.

2. Prevention of decay in large, treated timbers.

3. Evaluation of condition of all-wood foundations following long-term use.

4. Environmentally safe means of protecting plenum housing from subterranean termites.

5. Adequacy of treatment for aboveground wood components.

6. In-place remedial treatments for deteriorating wood members.

7. Advisability of using wood obtained from dead, standing timbers for construction purposes.

8. Rate of decay in large, structural members under in-use conditions.

9. Documenting annual losses in wood products due to biological agencies.

Some pertinent background information as well as research studies proposed are provided for each of the above areas in need of investigation, as follows:

Nondestructively Determining Strength of Deteriorated Wood In Use

Background.--Safety and economy dictate that a reliable means of strength-testing deteriorating structural members, in-place, be devised. For many years work has been conducted to develop methods for detection of interior rot in timbers. These methods have ranged from the primitive "sounding" of wood, to the extraction and inspection of wood borings, to use of mechanical probes, and finally to use of more sophisticated methods entailing X-ray and sonic equipment (Eslyn 1968). Ultrasonic pulse velocity tests have been investigated as a means of assessing wood strength (Lee 1965) as have other instruments used for measuring pulse transit times (Gerhards 1978; Kaiserlik 1978). In recent years a new method of detecting discolored and decayed wood has been developed which is based on the principle that resistance to a pulsed current decreases as concentrations of cations increase in wood and that cation concentrations increase in wood undergoing staining and decay (Shortle & Shigo 1973). The instrument developed for this work, termed a "Shigometer," has been tested on both living trees and utility poles (Shigo & Shigo 1974). Another recent innovation has been the development of a new nondestructive shock resistor tester, termed a "Pilodyn," used for detection of soft rot in utility pole exteriors (Friis-Hansen 1978; Hoffmeyer 1978). This instrument "shoots," under spring loading, a blunt pin into wood using an exact amount of energy. The depth of penetration of the pin is read directly on a scale. The Pilodyn is considered to be useful for prediction of wood strength (Friis-Hansen 1978). Studies are presently underway at the U.S. Forest Products Laboratory (FPL) aimed at determination of usefulness of the Pilodyn and the James Electronics V-Meter in estimating strength of mine timbers undergoing exterior decay.

Research Proposed.--Evaluation of strength of timbers, containing varying amounts of internal decay, utilizing instruments for measuring pulse transit time in wood.

Thermogravimetry appears a promising method for evaluating fungal attack of wood (Beall et al. 1976). Further testing of this method for possible usefulness in determination of strength of deteriorated wood is suggested.

Preventing Decay in Large, Treated Timbers

Background.--Since about 1950, the practice of air-seasoning timbers before preservative treatment has been progressively replaced by other forms of conditioning, as adequate air-seasoning of large timbers takes months and even years. Boiling in oil under vacuum (Boultonizing) has become a more common practice used with Douglas-fir timbers. Generally, no more water is removed than is necessary to obtain the specified preservative penetration and retention (Eslyn & Clark 1979). Large treated members, used for bridges, wharves, etc., are produced, therefore, which are put into use with interior moisture contents well above fiber saturation. As these timbers dry in use, they often develop seasoning checks that expose untreated interiors to infection and subsequent decay by wood decay fungi.

To prevent decay from occurring in checked timbers, Highley and Scheffer (1978) flooded the checks with different wood preservatives. Seven years later all timbers given such supplementary treatments contained active decay in the area of the checks. Apparently decay originated prior to treatment or the checks deepened after treatment and exposed untreated wood to infection.

Excessive checking in Douglas-fir spar crossarms was found by Graham & Estep (1966) and Ruddick & Rose (1979) to be preventable by cutting a saw kerf to the center of the wood member. Kerfing also reduced checking and splitting in guardrail posts and crossties (Graham 1979); hence, this method seems to have promise in prevention of decay in large horizontal timbers.

The incising of Douglas-fir poles to a depth of 6 cm, instead of the usual 2 cm, was accomplished with a deep-incising machine (Best & Martin 1969). Greater use of this machine would likely decrease possibility of decay in utility poles and in pole buildings.

Research Proposed.--Determine efficacy of chemicals flooded into checks in prevention of decay in large, treated timbers. Supplementary treatment would need be done shortly after check formation and would need to be redone as checks deepen.

Determine usefulness of kerfing large, horizontal timbers, prior to treatment and placement into use, in prevention of large checks.

Investigate availability of deep incising equipment for use on squared timbers, as well as efficacy of protection obtained and cost/benefit ratio.

Evaluate Condition of Preservative-Treated, All-Wood Foundations In Use

Background.--The all-weather wood foundation basically is a pressure-treated plywood-sheathed stud wall below grade (American Plywood Assoc. 1973). Advantages of this type of building are that construction costs are less, construction can be undertaken at any time of the year, and the enclosed space is more like normal living space than like a basement.

In 1937, an experimental prefabricated house was constructed on a wood foundation at the Forest Products Lab site in Madison, Wis. The retaining wall, in this case, consisted of southern pine planks pressure-treated with creosote. Following 30 years in place, the building was dismantled and found to be generally free from typical wood decay (Bendtsen & Eslyn 1968). Soft rot was prevalent in the soil-abutting face of the planks, but never exceeded 6 mm in depth.

Four experimental houses with wood foundations were built in Canada in the 1960's. Two were treated with CCA, one with creosote, and one with penta. The creosote- and penta-treated foundations were examined 11 years later and found to be free of typical wood decay and soft rot (Sedziak & Unligil 1973).

Although data from experimental houses show that pressure-treated wood foundations perform adequately, there still remains some concern about their performance under different field conditions and under varying quality of treatment and construction. The need for good quality control by the treating industry to ensure high uniformity of treatment of each piece making up the wood foundation has been stressed by Gjovik and Baechler (1970).

As of 1973, it was reported that 2,000 houses with wood foundations had been built in the United States and 100 in Canada (Sedziak & Unligil 1973). The older of these houses should provide some indication as to the performance which can be expected from wood foundations.

Research Proposed.--A joint industry-Forest Service study of the older wood foundations has been proposed which would involve researchers at both the Southeastern Experiment Station and FPL. Both decay of wood and corrosion of fasteners would be studied.

Safe Means of Protecting Plenum Housing from Subterranean Termites

Background.--Plenum houses are buildings erected on slab-on-ground foundations with warm air heating ductwork under the slab. To prevent subterranean termite attack in houses, the soil upon which the house is to be built is poisoned before house construction. However, in plenum houses, insecticide vapors from the soil are conducted to the living quarters above via the ductwork below. Hence, we need to prevent infestation of plenum houses by subterranean termites by a method that will not harm the human tenants of the buildings.

Research is underway for control of subterranean termites through use of attractant wood baits containing minute amounts of

termiticides (Esenther & Beal 1979). Perimeter treatments of buildings with Mirex baits in Ontario (Ostaff & Gray 1975) proved quite effective in control of termites. At present, a substitute for Mirex is being sought for use with the baits. A successful search may well lead to use of an environmentally safe bait-block method in protection of plenum housing from subterranean termites.

Research Proposed.--Continue search for a safe pesticide to use in bait blocks. Ultimately, test efficacy of method for protection of plenum houses from subterranean termites.

Entomologists at the Forest Service, Gulfport, Mississippi Laboratory have proposed (personal communication) the following two studies:

> Determine if the vapors penetrating soil covered with a vapor barrier are sufficient to be a health hazard, and
>
> If the health hazard is real, then testing of other less permeable vapor barrier materials should be instituted.

Adequacy of Treatment for Aboveground Wood Components

Background.--Long-term field trials of dip treatment of simulated wood joints show these simple preservative treatments to effectively protect different woods, in various climates, from decay (Scheffer et al. 1971; Scheffer & Eslyn 1978). These same trials showed significant variation in decay rate by climate of test site. Drawing upon data such as these, Scheffer (1971) devised a climate index for estimating potential for decay in aboveground wood structures.

Recently, Feist & Mraz (1978) showed that a water-repellent treatment alone was effective in protecting millwork from decay for the full 20-year period of their test. However, the test was conducted in Madison, Wis., where the decay hazard, according to Scheffer (1971), is only moderate.

We need to test various treatments--with emphasis on environmentally safe treatments--under different climatic conditions and subjected to varying microbial populations (species), to determine the least toxic treatment necessary for protection of wood under given use conditions.

Research Proposed.--Extend investigation of water-repellent treatment of wood to more severe (decay-wise) climatic conditions.

Investigate efficacy of new, environmentally safe chemicals for protection of wood aboveground.

Determine succession of micro-organisms involved in decay of different wood under different climatic conditions.

Prepare recommendations regarding need for and type of treatment for wood in use under different environmental conditions.

In-Place Remedial Treatments for Decaying Wood Members

Background.--Partridge (1961) showed that the oak wilt fungus could be eradicated from oak logs by exposing the logs to fumes of methyl bromide or chloropicrin. Carbon tetrachloride, formaldehyde, Mylone, and Vapam proved somewhat less effective. More recently, decay fungi were reduced in population or eliminated entirely from interiors of Douglas-fir poles one year after treatment with the fumigants Vapam, Vorlex, or chloropicrin. Decay fungi populations remained low for at least eight years after treatment. Fumigant vapors were found to move about 2.5 meters below and somewhat less above the point of treatment on the poles (Graham 1979).

Fumigants were also found to effectively eliminate decay fungi active in Douglas-fir bulkhead piles and laminated arches (Graham 1979).

Work is presently underway at FPL to determine efficacy of chloropicrin and Vapam in eradication of eight important decay fungi implanted in Douglas-fir wharf curbs (horizontal timbers).

While fumigation has been found to be effective in elimination of decay fungi in Douglas-fir, the author is aware of no other publications dealing with similar investigations on other woods.

Research Proposed.--Efficacy of fumigants in eradication of decay fungi in major construction woods, other than Douglas-fir.

Testing of other fumigants, less toxic than those previously investigated, for possible usefulness in eradication of decay fungi in wood.

Preparation and testing of fumigants in solid rather than liquid form to facilitate treatment of wood and decrease possibility of spillage of chemicals. Work of this nature is presently being undertaken at Oregon State University by Dr. M. E. Corden with solid methylisothiocyanate (Graham 1979).

Investigation of role of nondecay fungi and bacteria in prevention of reinfestation of fumigated timbers by decay fungi.

Using Wood Obtained from Dead, Standing Timber for Construction Purposes

Background.--An epidemic of the mountain pine beetle initiated in the late 1950's has spread throughout the lodgepole pine forests of western Wyoming and eastern Idaho and decimated many sawtimber-size stands (Tegethoff et al. 1977). Recently, an outbreak of this beetle has affected more than 647,000 hectares of forest land in northeastern Oregon (Harvey, Jr. 1979). In the southern United States, infestations of the southern pine beetle were estimated to occur on approximately 20.8 million hectares of forest land as of 1974 (Levi and Dietrich 1976). In the northeast, mortality of fir and spruce, due to spruce budworm attack, has been of primary concern. If mortality due to other insects, diseases, and fire were added to the above losses, the results would show enormous stands of dead trees throughout much of the timberlands in the United States.

While many studies have been conducted on volume losses due to decay in both downed and dead stands of trees, little has been done to determine strength losses and their effect upon potential for utilization in such trees.

Research Proposed.--More work need be done such as that by Sinclair et al. (1979) on toughness of salvaged southern pine and that by Tegethoff et al. (1977) on utilization of beetle-killed lodgepole pines for utility poles. The need for such investigations and the problems associated with utilization of salvaged timber are discussed by Levi and Dietrich (1976) and Snellgrove and Fahey (1977).

Rate of Decay in Large Structural Members Under In-Use Conditions

Rate of wood decay studies are generally carried out in the laboratory utilizing small pieces of wood. Exceptions to this are, for example, the preservative tests carried out on constructional timber in a "Schwammkeller" (fungus cellar) (Gersonde 1962) and those conducted on posts set in the ground (Davidson 1977). The need exists for decay studies to be conducted, particularly in aboveground situations, on construction-sized timbers.

Annual Losses in Wood Products Due to Activity of Biological Agencies

Presently used figures representing wood product losses due to action of micro-organisms, insects, and marine animals are far outdated. In addition, most appear to be based upon an insufficient and/or unknown data base. To set research priorities and to obtain funding for this research, we need up-to-date and reliable data on losses encountered in different wood products due to attack by various biological agencies. To compile such data will require, amongst others, the input of economists and those involved in maintenance and repair of wood structures.

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DECAY IN STRUCTURES: DIAGNOSIS, EVALUATION AND PREVENTION[1]

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ABSTRACT

A listing is provided of the author's recognition of existing research results in the area of diagnosis, evaluation and prevention of decay in structures as well as areas recognized as being in need of research before modeling of the decay process in buildings could be attempted.

IDENTIFICATION OF PERTINENT RESEARCH RESULTS ALREADY AVAILABLE

1. Laboratory and field evaluation of natural decay resistance of heartwood of U.S. commercial species in ground contact.

2. Laboratory and field evaluation of presently available preservative treatments for ground contact and above-ground exposure.

3. Chemical, mechanical and microscopical changes in wood resulting from decay.

4. Effects on strength of early stages of decay.

5. Requirements for decay and sources of inoculum.

IDENTIFICATION OF RESEARCH NEEDED TO MODEL THE DETERIORATION PROCESS OR TO EFFECTIVELY DIAGNOSE, EVALUATE AND PREVENT DECAY IN STRUCTURES

A. Evaluation of natural decay resistance of heartwood of U.S. commercial species in above-ground exposure and under fluctuating moisture conditions

B. Rate of decay and progression of decay in large, solid members of major construction species

C. Microscopical detection and evaluation of early stages of decay

D. Field diagnosis of decay

E. Non-destructive detection of early and advanced stages of decay

F. Role of insulation and vapor barriers in promoting decay

G. Role of water-repellent surface treatments in retarding or preventing the onset of decay

H. Generation of survey or estimated data on the volume or value of wood products used to replace deteriorated wood in structures. (These data are essential for securing public and governmental support in amount appropriate to the magnitude of the problem for wood deterioration and protection research.)

I. Continued research on the protection of wood from decay and insect attack using non-chemical means or by using chemicals not noxious to humans or those active in inconsequential quantities (behavioral chemicals, repellents, water repellents, desiccants, etc.)

PROPOSED COOPERATION

The author is currently involved in extensive research on item C and limited

[1]Paper presented at the Workshop of Research Needs on Effect of the Environment on Design Properties of Lumber, Forest Products Laboratory, Madison, Wisconsin, May 28-30, 1980.

research on item E. Plans are made for undertaking limited research on item B. The author would be interested in participating in cooperative research in any of the listed areas.

INFLUENCE OF CHEMICAL ENVIRONMENT ON STRENGTH OF WOOD FIBERS[1/]

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At first glance the title of this paper may seem to be out of place in a symposium on "Research needs on effect of the environment on design properties of lumber." When studying the effects of chemical environment on strength properties of wood, the first consideration is to look at the source of strength in wood. The strength component of logs, poles, lumber, etc. is the wood fiber. Softwood fibers are about 3.5 mm long and 0.035 mm in diameter while hardwood fibers are shorter (1-1.5 mm) and smaller (0.015 mm) in diameter. In wood, these fibers are glued together with a phenolic adhesive (lignin). Figure 1 shows a group of fibers with the lignin adhesive removed and Figure 2 shows naturally occurring fibers embedded in the lignin adhesive.

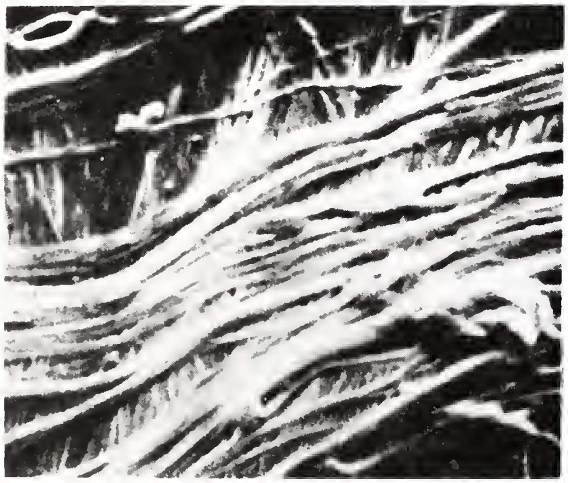

Figure 1.--Photomicrograph of delignified softwood fibers. X20,000

Figure 2.--Photomicrograph softwood fibers still embedded in lignin. X5,000

These fibers are long tube-like filaments composed of polymers (cellulose, hemicellulose and lignin.) Figure 3 shows the various cell wall layers and their composition of cellulose, hemicellulose and lignin. Cellulose is a polymer composed of glucose units linked β 1 $\rightarrow$ 4. The degree of polymerization (DP) or the number of glucose units in the polymer (n) in Figure 4 is quite large. This large polysaccharide molecule is mainly responsible for the strength component of the wood fiber. The hemicellulose (Figure 5) is a collection of polysaccharides somewhat smaller than cellulose that are composed mainly of xylose, glucose, galactose and mannose. The contribution of the hemicelluloses to the strength of the wood fiber is largely unknown. Lignin (Figure 6) is a complex phenolic polymer and is a component of cell wall as well as the major component of the middle lamella. The contribution of lignin to the strength property of the wood fiber probably resides in its role as an adhesive both inside the cell wall as well as bonding the fibers together.

[1/] Paper presented at the Workshop of Research Needs on Effect of the Environment on Design Properties of Lumber, Forest Products Laboratory, Madison, Wisconsin, May 28-30, 1980.

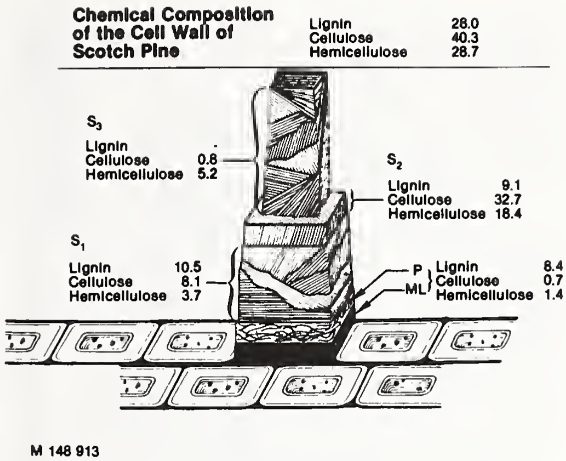

Figure 3.--Chemical composition of the cell wall of Scotch pine.

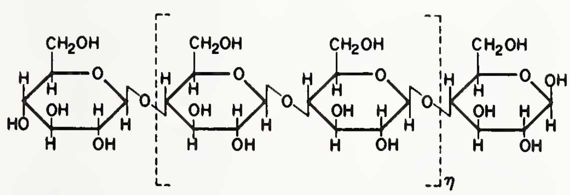

Figure 4.--Chemical structure of cellulose.

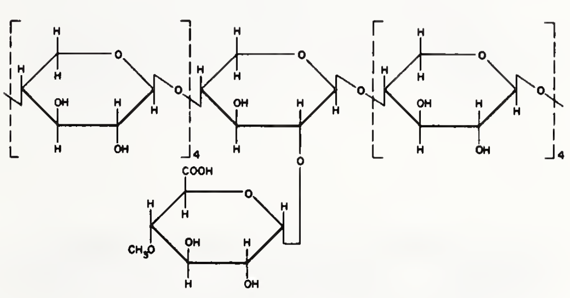

Figure 5.--Partial chemical structure of hemicellulose.

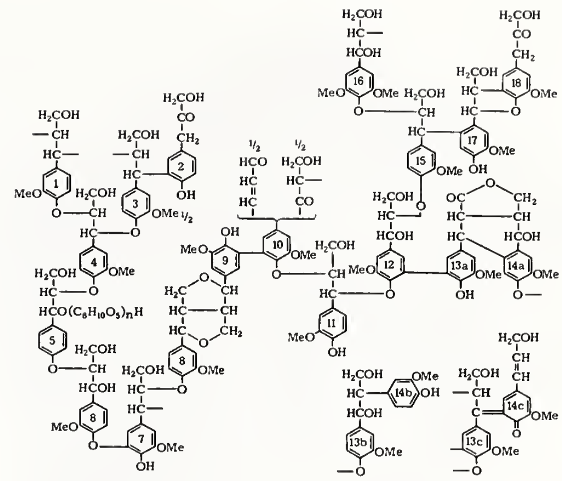

Figure 6.--Partial structure of softwood lignin.

It is important to know the chemical makeup of the wood fiber so one can anticipate the chemical reactions that are likely to take place as the fiber's chemical environment is altered. These reactions are easier to visualize if wood is studied as a polymer composite composed of cellulose, hemicellulose and lignin rather than as wood which chemically is a rather ambiguous nondescript term. This may seem self-evident but it is interesting to observe in the scientific literature that research results on chemical reactions of wood would have been easier to interpret if the substrate (wood) had been considered as a polysaccharide-phenolic composite rather than as wood.

Finally, if the polymer composite is considered in its three dimensional form, it will help visualize the total chemical makeup of the wood fiber. Figure 7 shows a cross section of many softwood fibers. The cell wall and middle lamella comprise the polymer composite or solid phase of the strength component while the voids or gas phase can be considered as storage tanks for chemicals. These voids, mainly lumens, can hold a considerable amount of chemicals. In southern pine early wood with a density of 0.33 g/cm^3 the void volume is 2.3 cm^3/g of wood. Late wood with a density of 0.70 has a void volume of 0.74 cm^3/g of wood (22.)

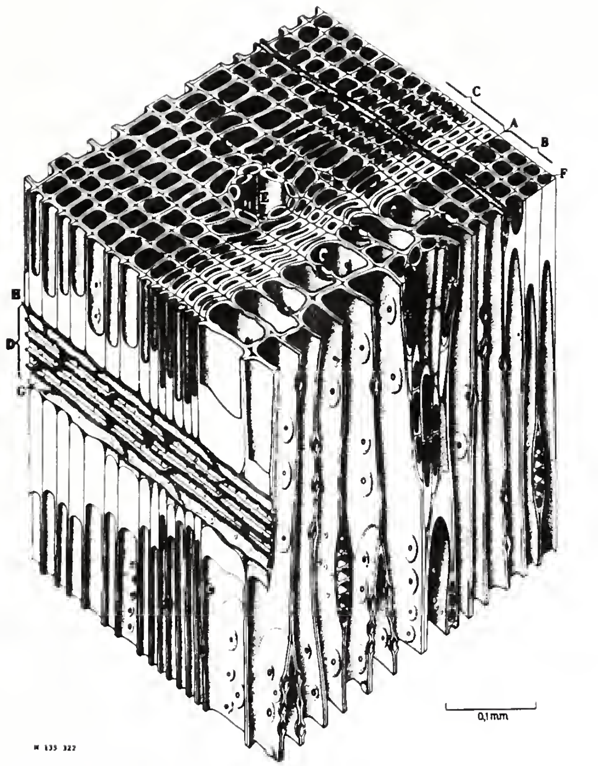

Figure 7.--Microstructure of softwood cross section.

Chemical environment of wood fiber

When considering the chemical reactions likely to take place in polysaccharide and phenolic polymers in the wood fibers, the chemical environment the fiber is in is of great importance. The chemicals that can be stored in the cell wall and voids in the wood can swell, hydrolyze, pyrolyze, oxidize and, in general depolymerize these polymers thus causing a loss in strength properties due to the degradation of the wood fiber network. The change in environment of the fiber that may take place can be classified in two categories: (1) natural changes in environment and (2) planned changes in environment.

1. Natural changes in the chemical environment of the wood fiber.

a. pH. The average pH of wood is between 3 and 5.5 (28). The acidity is due to the acetyl content, the presence of acid extractives and the absorption of cations of the salts that comprise the ash. This mild acidic condition does not cause any appreciable strength losses even after several hundred years so long as the wood is protected from biological attack (30).

If the pH of wood changes due to a variety of causes, strength properties can be reduced. In general, heartwood is more resistant to acid than sapwood. Hardwoods are more susceptible to degradation by both acids and alkalies than softwoods. Oxidizing acids, such as nitric, have a greater degradative action on wood fiber than nonoxidizing acids. Alkaline solutions are more destructive to wood fibers than acidic solutions (30). Wood absorbs alkaline solutions more readily than acidic solutions. Acids with a pH above 2 and bases with a pH below 10 do not degrade the wood fiber to a great extent over short periods of time at low temperatures (14). Early research showed that mild acids such as acetic had little effect on strength while strong acids such as sulfuric acid caused extensive strength losses (1).

b. Swelling solvents.--Solutions which swell wood tend to plasticize wood and reduce the strength properties. In general, the greater the swelling that the wood undergoes, the greater the strength loss. Non-swelling liquids do not decrease strength properties. For example, ovendry wood and wood saturated with water-free benzene have virtually the same strength (8).

c. Adsorption of elements from the environment.--The effects of adsorbed acids and bases from the surrounding environment have already been discussed. Other chemicals can also be absorbed that cause degradation of the wood fiber. For example, Figure 8 shows a micrograph of a piece of southern pine that has been exposed to the ocean air. It can be seen in the far left of the picture that the fibers are badly degraded. A closer look (Fig. 9) reveals that salt crystals have deposited in the void structure. These cause extensive chemical and physical damage.

Other salts can be absorbed from the environment. Iron, from metal fasteners, as it is oxidized can be absorbed and cause decomposition of the cellulose. This is also true of copper, chromium, tin, zinc, and other metals.

d. Ultraviolet degradation.--Wood exposed outdoors undergoes chemical reactions due to UV radiation. The UV radiation causes photochemical degradation primarily in the lignin component which gives rise to characteristic color changes. Southern pine, for example, changes from a light yellow natural color to brown, and eventually to gray (Fig. 10). Since the lignin is acting as an adhesive in the wood, as the lignin degrades the wood surface becomes richer in cellulose content. Cellulose is much less susceptible to UV degradation (12). The cellulose is then washed off the surface with water during a

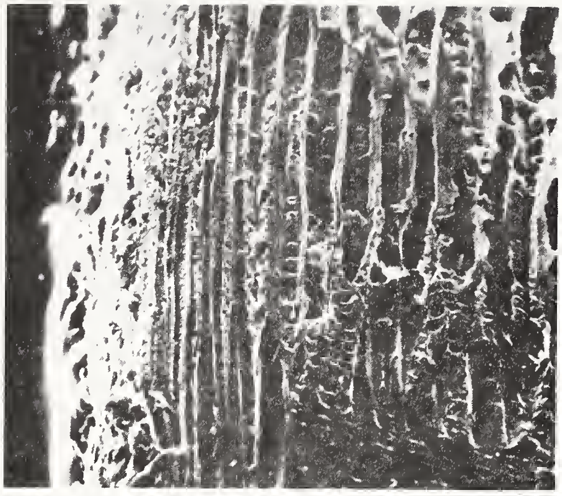

Figure 8.--Photomicrograph of NACl deposited in southern pine. X50

Figure 9.--Photomicrograph of NaCl deposited in southern pine. X500

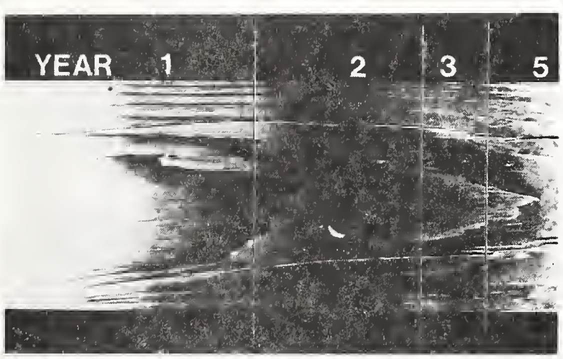

Figure 10.--Color changes in southern pine due to weathering.

rain exposing new lignin which then starts to degrade. As this process continues, the wood surface is said to "weather." Weathering can account for a significant loss in surface fiber in time (Fig. 11).

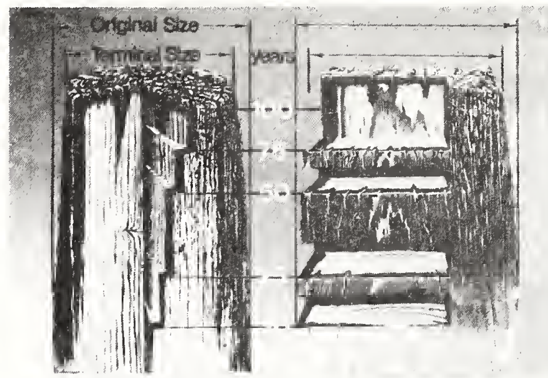

Figure 11.--Wood loss in southern pine due to weathering.

Weathering is a surface phenomenon since UV radiation does not penetrate wood more than a few cells deep, but as the degradative process continues, the loss in fiber can account for some degree of strength loss.

e. Heat.--In general, there are two types of effects heat has on wood. Effects that occur only as long as the changed temperature is maintained and permanent effects resulting from thermal degradation of the polymer components. Low temperatures have very little effect on wood strength. For example, freeze dried wood at minus 50°C has essentially the same modulus of elasticity (MOE) as wood at room temperature (14). Nearly a linear decrease in strength is observed in the temperature range of minus 200°C to plus 160°C. Over this temperature range the loss in strength is two to three fold (14).

The initial effects of heating wood is dehydration. As the temperature gives higher hemicellulose and cellulose depolymerization begins to occur. Pyrolysis and volatilization of cell wall polymers occur at about 250°C followed by char formation in the absence of air and combustion in air.

Heating Douglas-fir at 102°C for 335 days reduced MOE by 12%, modulus of rupture (MOR) by 28%, and fiber stress to proportional limit by 18% (16-18). The same losses would be observed in one week at 160°C. In the absence of air, heating softwood at 210°C for 10 minutes reduced MOR by 2%, hardness by 5% and toughness by 5% (27). At 280°C under the same conditions, MOR is reduced 17%, hardness 21% and toughness 40%.

Figure 12 shows a cross section of southern pine early wood and late wood at 25°C. Figure 13 shows the same sample after heating to 295°C in the absence of air. It can be seen in Figure 13 that the cell structure is still in tact but pyrolysis has darkened the cell wall components. Even though the cell structure still appears somewhere normal (except for the darkening) the strength properties are greatly reduced due to the thermal degradation of the wood fiber.

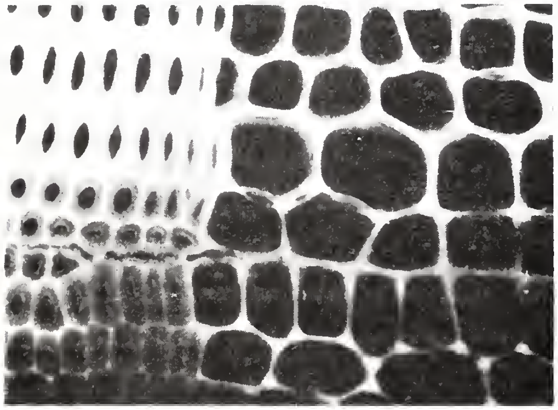

Figure 12.--Photomicrograph of southern pine late wood and early wood at 25°C. X500

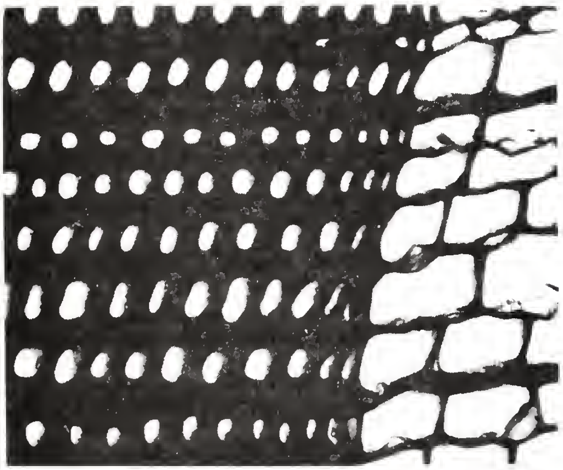

Figure 13.--Photomicrograph of southern pine late wood and early wood after heating to 295°C. X500

f. Biological degradation.--When organisms come into contact with wood, they can cause several types of degradation of the cell wall polymer to occur. The mechanical damage caused by eating can result in significant losses in strength. Chemical reactions such as hydrolysis by acids and enzymes, dehydration and oxidation can also degrade the wood fiber. It is well known that biological attack can result in major losses in strength. It can be seen in Figure 14 that in the initial 10% weight loss due to a brown-rot fungi on southern pine the drop in DP of the holocellulose (hemicellulose and cellulose combined) is from 1500 to 300 or a 5-fold drop (5). As the polymers responsible for strength in the wood fiber are degraded, mechanical properties of the wood decrease.

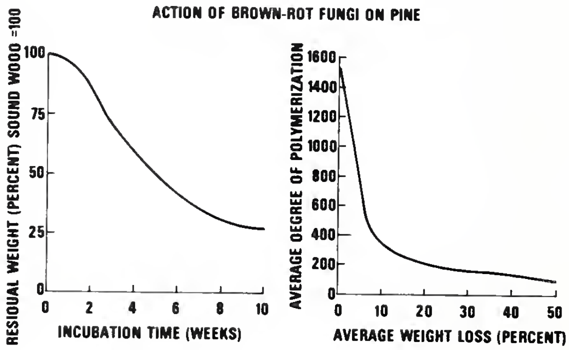

Figure 14.--Action of brown-rot fungi on pine (5).

The large drop in DP represents a large drop in strength properties of wood and very little weight loss occurred. These results would indicate that at least in the initial biological attack, hydrolytic chemical reactions play an important part. These chemical reactions in this phase of degradation are breaking very large polymers into smaller more digestible pieces. It has been suggested that hydrogen peroxide and iron are the cause of this rapid depolymerization (13). It is possible that the initial attack by micro-organisms is not only enzymatic but hydrolytic and oxidative in nature.

g. Naturally occurring chemicals in wood.--Some woods have a higher acidic extractive content that can cause greater strength losses due to hydrolysis. This may be a problem in some of the tropical species coming into the market. These more acidic woods will not only affect strength, but will increase the corrosion of fasteners used in the wood.

Naturally occurring crystals in wood (Fig. 15) can also cause strength losses due to abrasion of the fibers, increased hygroscopicity and hydrolysis when these salts dissolve. It is not uncommon to find silica and calcium salt crystals in the wood fiber particularly in tropical species.

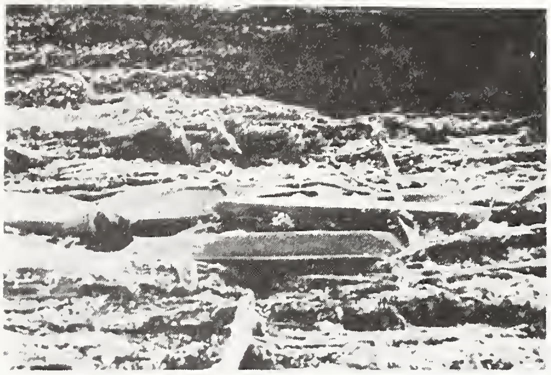

Figure 15.--Photomicrograph of $CaCO_3$ crystals deposited in lumens of southern pine. X1000

2. Planned changes in the chemical environment of the wood fiber.

a. Salt treatment for rot resistance.--Salts such as chromated copper arsenate (CCA), ammoniacal copper arsenite (ACA) along with other metals such as zinc and tin are used to increase the service life of wood in use against biological attack. These salts increase the hygroscopicity of wood and at high concentration are sufficiently acid in nature to cause some hydrolysis (3,10). Studies with CCA and ACA treated southern pine and Douglas-fir show 20-50% losses in MOR, MOE and compressive strength (7).

These precipitated salts can be seen in the wood structure Figure 16 in a photomicrograph of untreated southern pine. Figure 17 is a photomicrograph of southern pine treated with 0.5 lb of CCA per ft^3. The salts appear as a rough coating on the lumen walls.

Preservative formulations which contain copper and chromium salts promote afterglow in treated wood. If the treated wood starts to burn, glow or smoulder even if no flame is present, the wood may continue to glow until the entire member is gone (6,15). This could cause serious problems in utility poles, fence posts and highway signs, for example, when grass is burned around the structure.

Just as with acids in wood, high salt retentions will cause fasteners to deteriorate at a much faster rate (2).

b. Salt treatment for fire retardancy.--Salts such as sodium tetraborate, diammonium phosphate, trisodium phosphate, diammonium sulfate and salts of boric acid have long been used as fire retardants. Problems of hygroscopicity, corrosion of fasteners and increased acidity are also a problem with salts used for fire retardancy. The salts also precipitate in the cell wall as can be seen in Figure 18. Here they are shown on the fiber surface of pine treated with 4.2 lbs/ft^3 of ammonium dihydrogen phosphate. Because of the hygroscopicity of many fire retardant salt treatments, they are not recommended for use where relative humidity is over 60% (11).

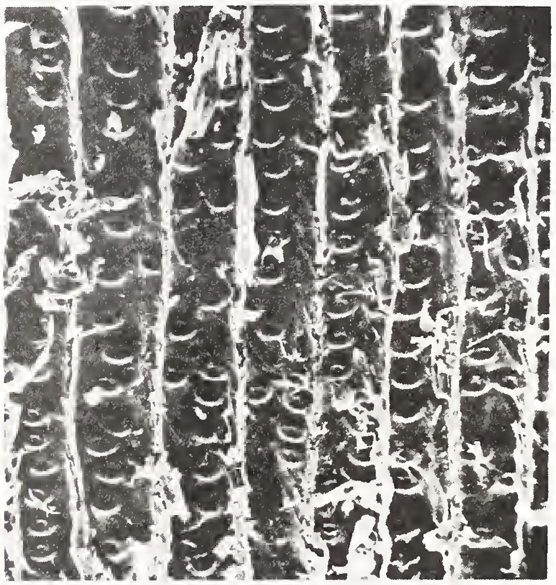

Figure 16.--Photomicrograph of longitudinally split southern pine. X200

Figure 17.--Photomicrograph of southern pine treated with 0.5 155/ft^3 of CCA. X200

Figure 18.--Photomicrograph of southern pine fiber treated with 4.2 lbs/ft^3 of $NH_4H_2PO_4$. X2000

Several studies have shown that strength properties of fire retardant salt treated wood have been reduced. Average losses in kiln dry small clear specimens were 13% in MOR, 5% in MOE and a significant loss in work to maximum load (9). The effects on strength are greater in kiln dried salt treated wood than in air dried salt treated wood (4). This may be due to acidic degradation of the fiber caused by the acid salts.

c. Chemical modification of cell wall components.--The hemicelluloses and cellulose which serve as a food source for microorganism can be chemically modified so the organism no longer recognize them as food. Bonding epoxides, isocyanates, anhydride, lactones, nitriles and other reactive chemicals to cell wall components, gives a modified wood which is resistant to attack by termites, fungi and to marine borers in laboratory tests (20,21,23,24,25).

Preliminary results on chemically modified maple show a loss of 14% in MOE and 17% in MOR. Since the chemicals react in the cell wall, the treated wood swells to accommodate the added chemical. As was noted earlier, any time swelling occurs in wood there is a corresponding loss in mechanical properties.

d. Lumen fill polymer treatments.--Up to now, only treatments to wood that caused a decrease in mechanical properties have been presented. It is possible to treat wood with organic monomers and polymerize them in the void structure and increase the strength of wood. Figure 19 shows a cross section of eastern white pine treated with tritium-labeled methyl methacrylate. The autoradiograph shows that the lumen is filled with polymer (29).

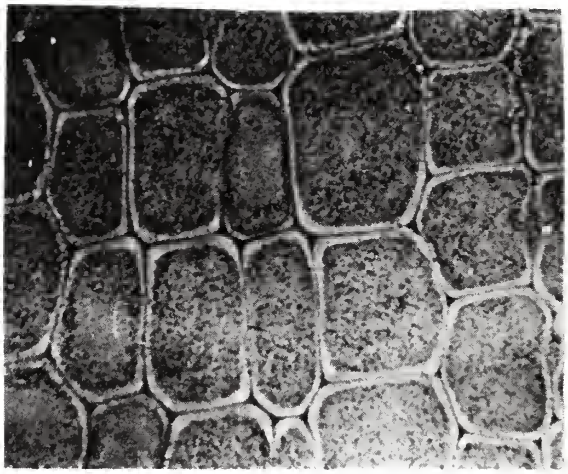

Figure 19.--Photomicro autoradiograph of wood filled with tritium-labeled methyl methacrylate. X300

Hard maple treated to a 67% polymer weight add on, shows an increase in MOE of 21% and of 33% in fiber stress as proportional limit (19). Hardness tests on similar samples showed an increase of 20% in radial hardness, 186% in tangential hardness and 76% in longitudinal hardness (26).

This type of technology is actually adding another polymer in polymer composite of cellulose, hemicellulose and lignin. It is possible to add chemicals to the system and polymerize them in the lumen polymer matrix which could improve rot resistance, fire retardancy and other desirable properties of wood.

Conclusions

There has been a great deal of research on strength losses in wood as a result of a change in chemical environment, however, it tends to be fragmented and designed to answer a specific question. This research has been of the observative type--do something and see what happened. What is needed is a systematic research program designed to determine the mechanism of strength loss as a function of the woods environment. When this has been done, there would be a data base generated that would allow one to predict the degree of degradation related to a particular environmental factor and be able to determine the extent of strength loss.

There are some specific studies that might be suggested in this general area.

1. Establish a test or set of tests that best describes the mechanical losses in wood as a result of an environmental change.

2. Determine the effects of pH, temperature, metals, and moisture specifically as they relate to strength losses in wood.

3. Correlate all data on strength losses due to hydrolysis (biological, pH and metals), pyrolysis (heat and fire) and oxidation (chemicals) to degradation of cell wall polymers.

4. Correlate losses in degree of polymerization of cellulose and lignin modification with strength loss.

5. A great deal of strength is lost in the initial (less than 10% weight loss) attack by microorganisms. The mechanism of this strength loss may be related to oxidative reactions which quickly depolymerize cellulose. A study should be conducted to determine what is happening to the fiber during the initial biological attack.

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RESEARCH NEEDS ON TEMPERATURE AND MOISTURE FACTORS

REPORT OF THE TASK GROUP

A. Immediate effect of temperature and moisture content on properties of lumber.

1. The effect of temperature and moisture content on lumber properties is potentially greater in high-grade material. Also, design is closer to life safety limitations in the higher grades. Therefore, research on these effects should initially concentrate on higher grades (#1 and above) in thinner (2-inch) dimension where the effects and the hazard potentials are greatest.

2. Research is needed to determine if the immediate effect of temperature is reversible in lumber, and to determine how constant and variable moisture contents affect this behavior. The effect of rewetting previously dried low-grade lumber on EI is not known.

3. More research is needed on the effect of moisture content on properties of lumber in tension parallel to the grain. Current design practice is inconsistent with some available data on small clear specimens, and the effect on lumber is not known.

B. Permanent effect of temperature and moisture content on properties of lumber.

1. The effect of high-temperature drying in terms of method and the resulting moisture gradient on strength needs to be investigated. This research should initially concentrate on a few major structural species.

2. Little is known about long-term constant temperature conditions. This effect should be investigated for lumber.

3. There is a need, in some climates, for information on low-temperature effects in lumber.

C. Effect of cyclic temperature and relative humidity on properties of lumber.

1. Additional research is needed for both clear wood and lumber. Research is needed to evaluate the effect of cyclic humidity with the load applied only during the desorption, and only during the adsorption portion of the cycle.

2. Additional studies are needed to determine the effect of cyclic temperature and moisture content, based on schedules that exist in structures, on lumber properties.

3. The effect of cyclic conditions on creep of lumber in bending and on creep-rupture in tension should be further investigated.

D. Sensitivity studies, with calibration to known data points, to identify areas of greatest potential for improving performance are needed in order to select and prioritize experiments. The objective of the research should be to provide a data base for developing and calibrating a model for predicting performance.

E. Research needs on treated lumber were discussed. Recommendations follow those from the task group on biological and chemical factors.

Dave Barrett
Chuck Gerhards
Dave Green
Duane Lyon, Chairman
Lisa Marin
Erv Schaffer
Stan Suddarth

ADJUSTING THE STATIC STRENGTH OF LUMBER FOR CHANGES IN MOISTURE CONTENT[1]

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ABSTRACT

Of the environmental factors which affect the mechanical properties of wood, one of the most important is moisture content. The development of standardized procedures for adjusting lumber strength for changes in moisture content is reviewed. Historically, the adjustment procedures for flexural properties in ASTM standard D 245-74 are shown to have been based on tests of lumber in structural sizes, with the magnitude of the adjustment being dependent upon the thickness and apparent strength of the piece. It is indicated that current adjustment procedures are based on mean strength properties that, when compared to tabulated average strength properties obtained from tests of full size lumber, were considered to be conservative for most species. A review of recent research results indicates that the magnitude of the seasoning adjustment for tensile and flexural strength of lumber is dependent upon the initial strength of the piece in the green condition. The need for an analytical model for describing the moisture content-strength relationship is stressed. Obstacles to the establishment of an effective model are discussed. Recommendations for future research in order to overcome some of these obstacles are given.

INTRODUCTION

Of the many environmental factors that affect structural design with wood, one of the most important is moisture content. Most of the mechanical properties of clear wood increase significantly as moisture content decreases (fig. 1). General discussions of the effect of moisture content on clear wood mechanical properties are given in several references (22,30,32)[3] and a comprehensive review of research findings has recently been compiled by Gerhards (14). Despite the volume of information available on clear wood properties, there is little definitive information available on the effect of moisture content on the strength of wood containing defects.

Both the United States and Canada are currently involved in large in-grade testing programs (11), the primary objectives of which are to characterize the mechanical properties of existing grades of dimension lumber. So

[1] Paper presented at the Workshop of Research Needs on Effect of the Environment on Design Properties of Lumber, Forest Products Laboratory, Madison, Wisconsin, May 28-30, 1980.

[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[3] Underlined numbers in parentheses refer to literature cited at end of this report.

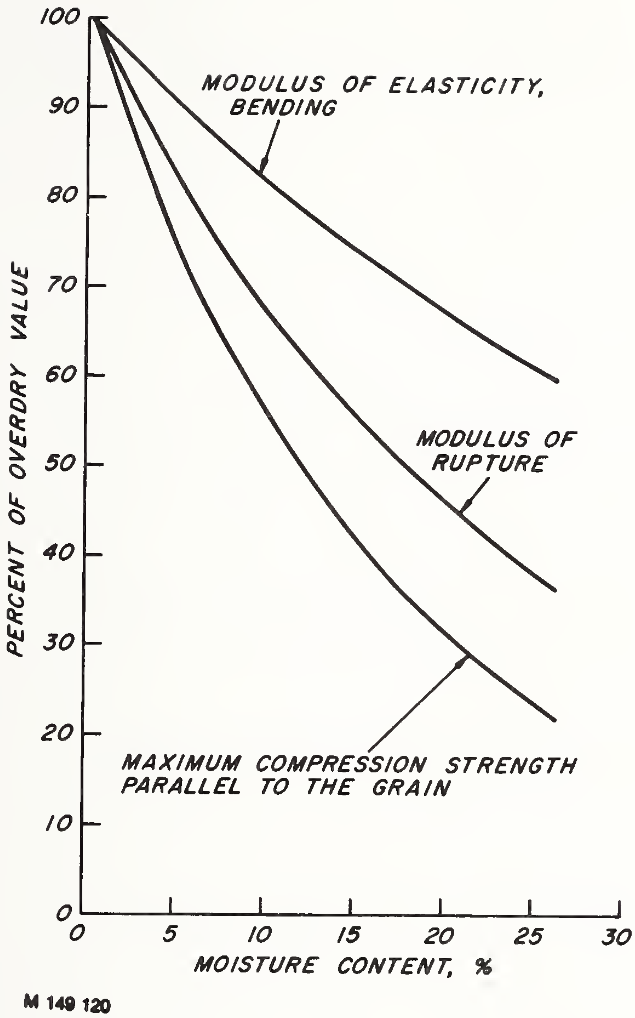

Figure 1.--Effect of moisture content on the strength of clear wood (30).

that these characterizations will relate to the properties of a grade as it is produced by the mill, all testing is being conducted at the mills, using portable equipment. As expected, the moisture content of this material varies significantly from mill to mill. To interpret how this material will perform at various end-use moisture conditions, and to correctly interpret the other causes of between-mill variations in properties, it may be necessary to adjust properties for changes in moisture content.

Current deterministic design procedures for lumber focus on the properties of the lower tail of the strength distribution. In the United States this procedure may be represented by an equation of the form,

$$F_{allowable} = F_{clear} \cdot \gamma_{gen} \cdot \gamma_{MC} \cdot \gamma_{grade} \cdot \gamma_{size} \quad (1)$$

where

$F_{allowable}$ = the allowable design stress from lumber

F_{clear} = the 5th percentile strength value obtained from green, small, clear specimens

γ_{gen} = the general adjustment factor for duration of load plus manufacture and use conditions (also called factor of safety)

γ_{MC} = adjustment for end use moisture conditions

γ_{grade} = minimum strength ratio for the grade of lumber being used

γ_{size} = adjustment for depth of member, if applicable.

The factor used to adjust green lumber strength for end use moisture conditions, γ_{MC}, is given in ASTM standard D 245-74 (1). For lumber that will be used at a maximum moisture content of 19 percent (average lot moisture content of 15 pct), the green bending and tensile strength is increased 25 percent. For lumber with a maximum moisture content of 15 percent (12 pct average) the increase is 35 percent.

The primary objective of this paper is to review the development of standardized concepts for describing the effect of moisture content on lumber strength and to relate this information to needs in wood engineering research.

THE DEVELOPMENT OF STANDARDIZED STRENGTH--MOISTURE CONTENT RELATIONSHIPS

Modulus of Rupture

In recognition of its potential importance, the effect of moisture was included as an experimental parameter in one of the earliest studies conducted by the U.S. Forest Service on the mechanical properties of structural lumber.

Table 1.--Ratios of average strength values for air-seasoned material to those for green material (5)

Species	Bending				Compression parallel to grain			Compression perpendicular to grain	Shear
	Fiber stress at elastic limit per square inch	Modulus of rupture per square inch	Modulus of elasticity per square inch	Horizontal shear per square inch	Crushing strength at elastic limit per square inch	Crushing strength at maximum load per square inch	Modulus of elasticity per square inch	Crushing strength at elastic limit per square inch	Shear strength per square inch
	Lbs	Lbs	1,000 lbs	Lbs	Lbs	Lbs	1,000 lbs	Lbs	Lbs
Longleaf pine:									
Structural sizes	0.99	0.94	1.16	0.77	1.00	1.00	--	1.01	--
Small specimens	1.36	1.27	1.13	--	--	--	--	--	1.01
Douglas-fir:									
Structural sizes	1.15	1.06	1.02	1.33	1.18	1.22	0.73	1.12	--
Small specimens	1.28	1.25	1.06	--	1.10	1.24	0.56	--	1.08
Shortleaf pine:									
Structural sizes	1.44	1.19	1.17	1.10	1.66	1.76	1.26	2.26	--
Small specimens	1.79	1.57	1.28	--	--	1.79	--	2.32	1.61
Western larch:									
Structural sizes	1.05	1.18	1.14	1.18	--	1.64	--	1.31	--
Small specimens	1.38	1.42	1.19	--	--	1.60	--	--	1.29
Loblolly pine:									
Structural sizes	1.16	1.19	1.07	1.30	1.47	1.46	2.20	1.31	--
Small specimens	1.26	1.19	1.02	--	--	1.71	--	--	1.77
Tamarack:									
Structural sizes	1.33	1.21	1.10	1.15	1.40	1.34	0.98	--	--
Small specimens	2.33	2.26	1.69	--	--	1.60	--	--	1.32
Western hemlock:									
Structural sizes	1.25	1.21	1.20	1.07	1.67	1.73	1.32	1.09	--
Small specimens	1.44	1.42	1.17	--	1.55	1.59	1.11	--	1.47
Redwood:									
Structural sizes	0.92	0.87	0.85	--	--	1.16	--	1.21	--
Small specimens	1.00	1.12	1.08	--	--	1.29	--	0.99	0.90
Norway pine:									
Structural sizes	1.63	1.57	1.25	1.20	1.48	1.66	1.36	--	--
Small specimens	1.88	1.64	1.21	--	--	3.01	--	--	1.94

The results of these studies are summarized in Bulletin No. 108 (5). Using data for bending, compression parallel and compression perpendicular to the grain (table 1), it was concluded that, although seasoning results in a significant increase in strength for small, clear specimens, for timber the increase in strength due to drying is offset by a weakening of the timber as a result of the formation of drying checks. Grading rules for structural timbers proposed by the Forest Service in 1915 show no allowable increase in strength properties due to seasoning (4).

A system of grading lumber much like that now in use is described in USDA Circular No. 295, published in 1923 (29). This system was based on the results summarized in Bulletin No. 108. No specific rules for seasoning adjustments are given in Circular No. 295; however, table 1 of that document presents permissible working stresses for three different moisture conditions; wet location, dry outside location and dry inside location. In an unpublished memorandum, J. A. Newlin and R.P.A. Johnson[4] discuss the factors involved in determining the working stresses given in Circular No. 295. They state that the checking, which accompanies drying, increases in severity with the size of the piece and the number and size of the knots present. For lumber thicker than 4 inches, it was concluded that the increase in strength was largely offset by seasoning degrade. After reviewing all the test results conducted at the Laboratory to that data on green and dry full-size lumber they concluded that some adjustment for seasoning was permissible for lumber 4 inches and less in thickness. The adjustments tabulated by Newlin and Johnson were dependent upon the grade of the lumber and are given in table 2. They further stated that "the lower grades of large timbers and about 25 percent of higher grades show no increase in strength with drying, although the average strength is raised slightly." In the appendix of the Newlin and Johnson memorandum, under "Modifications of and Additions to Circular No. 295 . . . Developed in Conference with Forest Products Laboratory," is the statement:

"The working stresses for dimension (lumber) not thicker than 4 inches may be increased proportionately over those for timbers in dry (sic) locations with corresponding defects from equal stresses in a grade having one-half the strength of clear wood to stresses 25 percent greater than in timbers in a grade of clear wood strength."

Although slightly more conservative than the increase cited by Newlin and Johnson in the main text, the "25 percent rule" closely approximates the Forest Products Laboratory results (table 2). With only editorial changes, the 25 percent rule was included in the 1930 revision of D 245 (1). For green lumber having a strength ratio of 50 percent or more this rule can be written as:

$$SR\ dry = SR\ green + 1/2\ (SR\ green - 50) \quad (2)$$

where

SR = strength ratio, percent.

Table 2.--Effect of moisture content on the mechanical properties of structural lumber 2 to 4 inches in thickness developed by the Forest Products Laboratory in the 1920's[a/]

Grade	Strength ratio,[b/] green condition	Increase in strength for dry location	
		Experimental evidence	25 Percent rule
S1	88	20	22
S2	75	15	17
S3	62	8	10
S4	50	0	0

a/ Adapted from memorandum by J. A. Newlin and R.P.A. Johnson filed in 1924 and entitled "A Discussion of Factors Involved in Determining Safe Working Stresses for Timber." From the unpublished records of the Forest Products Laboratory.

b/ Strength ratio based on 1923 concepts, approximately equal to strength ratio by 1980 concepts.

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In 1933, Wilson (33) discussed the effect of moisture content on the strength of wood. In this document, he proposed what has come to be known as the FPL exponential formula for correcting the strength of small, clear specimens for the effect of moisture content (32). Wilson also discussed the effect of moisture

[4] Memorandum by J. A. Newlin and R.P.A. Johnson filed in 1924 and entitled "A Discussion of Factors Involved in Determining Safe Working Stresses for Timber." From the unpublished records of the Forest Products Laboratory.

on the strength of structural lumber and drew the following conclusions:

(1) Tests of the strength of specimens with moisture nonuniformly distributed within the cross section may or may not be stronger, and could be weaker than would be expected from an average moisture content. The outcome appears to be species dependent.

(2) Tests of similar groups of green and seasoned lumber have shown that although maximum- and average-strength values are higher for the seasoned material, minimum values are not appreciably raised by seasoning.

The latter statement clearly supports Newlin and Johnson's[4] statement that 25 percent of the higher grades of large timbers show no increase in strength due to seasoning.

In 1947 Lyman Wood reviewed available Forest Products Laboratory data on the relationship between strength ratio, moisture content, and the strength of structural timbers.[5] Wood observed that the correlation between strength ratio and the increase in strength due to drying was fairly strong for Joists and Planks (lumber of rectangular cross section, 2 to 4 inches thick, and 4 inches or more in width), figure 2, but concluded that the correlation was not significant for Beams and Stringers (lumber of rectangular cross section, 5 by 8 inches and up), figure 3. Wood suggested that for Joists and Planks, the 25 percent rule might be modified to read "strength ratio . . . increased by its excess over 60 percent." He also recommended that a small increase in estimated strength be permitted for Beams and Stringers. Wood's conclusions were apparently based on a comparison between the green and dry <u>average</u> strength of full size lumber and the <u>average</u> strength ratio of each of 14 species (table 3).

The basic idea that the effect of moisture on the strength of dimension lumber is somehow dependent upon the quality (or strength) of the material was retained in D 245 through 1968. However, the interpretation of how this adjustment could be applied began to change. Standard D 245-49T (1) states that "in these sizes used in dry locations, higher working stresses in extreme fiber in bending can be permitted with the same size defects as in pieces of larger size, or greater defects can be permitted with

[5]Wood, L. W. 1947. Influence of drying on the strength of structural timbers. Office Report. From the unpublished records of the Forest Products Laboratory.

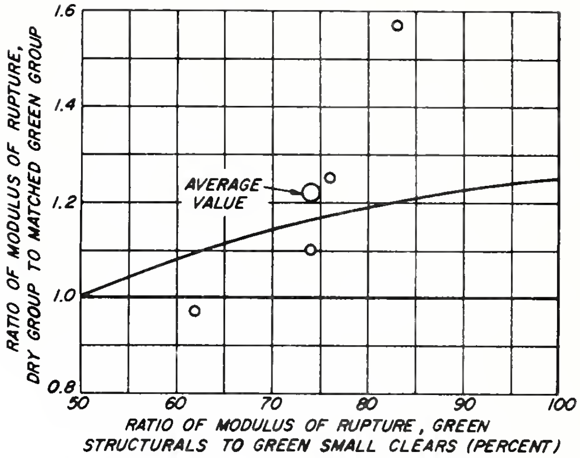

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Figure 2.--Relation of increase in bending strength for drying to strength ratio in various species groups of joists and planks. (Wood, L. W. 1947--see footnote 5.)

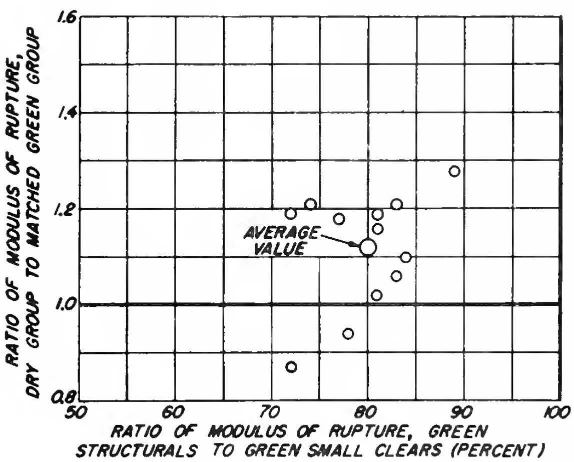

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Figure 3.--Relation of increase in bending strength from drying to strength ratio in various species groups of beams and stringers. (Wood, L. W. 1947--see footnote 5.)

the same working stress." It is further stated that the increase in strength due to seasoning is "commonly taken into account by increasing the strength ratio by half of its excess over 50 percent." Also, when one takes "advantage of the increase in strength from drying by increasing permissible sizes of knots or other characteristics rather than by increasing the working stress . . . the working stress may require reduction if the material is to be used under wet conditions." This interpretation is much more complex than the original principles

Table 3.--Comparison of green and dry bending strength averages for groups in various species[1/]

Species	Source of data[2/]	Green timber groups: Individuals in group	Average moisture content	Average specific gravity[4/]	Average modulus of rupture	Depth factor[3/]	Corrected modulus of rupture	Modulus of rupture of matched small clears	Ratio-green timbers to small clears	Matched dry timber groups: Individuals in group	Average moisture content	Average specific gravity[4/]	Average modulus of rupture	Ratio-dry timbers to green timbers
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
		No.	Pct		Lb/in.^{2}	Ratio	Lb/in.^{2}	Lb/in.^{2}	Pct	No.	Pct		Lb/in.^{2}	Ratio
JOIST AND PLANK GROUPS														
Douglas-fir (Rocky Mt.)	Proj. 256	26	28.0	0.46	3,600	0.888	4,050	6,490	62	25	12.5	0.46	3,480	0.97
Ponderosa pine	Proj. 256	23	41.4	0.44	3,920	0.888	4,410	5,830	76	23	12.4	0.45	4,890	1.25
Eastern hemlock	Proj. 211	52	96.9	0.42	4,010	0.908	4,420	5,970	74	53	13.5	0.42	4,420	1.10
Norway (red) pine[5/]	Bull. 108	33	49.0	0.40	3,860	0.898	4,300	5,170	83	10	15.2	0.43	6,050	1.57
Average of joist and plank groups									74					1.22
BEAM AND STRINGER GROUPS														
Sitka spruce	Proj. 189	20	34.2	0.41	4,160	0.872	4,770	5,360	89	20	17.3	0.40	5,310	1.28
Western hemlock	Proj. 189	28	41.6	0.49	4,950	0.872	5,680	7,000	81	28	17.5	0.48	5,750	1.16
Eastern hemlock	Proj. 211	18	110.2	0.41	4,630	0.930	4,980	6,150	81	16	13.1	0.43	4,700	1.02
Longleaf pine	Proj. 184	41	32.5	0.62	6,190	0.884	7,000	8,310	84	39	17.3	0.62	6,800	1.10
Longleaf pine	Bull. 108	19	28.7	0.56	6,140	0.872	7,040	9,070	78	15	20.7	0.63	5,750	0.94
Shortleaf pine	Bull. 108	48	47.4	0.48	5,550	0.884	6,280	7,710	81	13	16.2	0.50	6,570	1.19
Loblolly pine	Bull. 108	111	58.6	0.50	5,080	0.892	5,700	7,870	72	25	20.4	0.51	6,120	1.19
Douglas-fir (Coast)	Bull. 108	191	31.5	0.45	5,980	0.872	6,860	8,280	83	91	20,8	0.45	6,370	1.06
Western larch	Bull. 108	62	50.7	0.45	4,950	0.884	5,600	7,250	77	52	18.0	0.47	5,860	1.18
Tamarack[6/]	Bull. 108	30	50.6	0.48	4,560	0.906	5,030	6,820	74	9	19.2	0.50	5,500	1.21
Western hemlock	Bull. 108	39	42.5	0.43	5,300	0.872	6,080	7,290	83	44	17.7	0.45	6,420	1.21
Redwood	Bull. 108	28	86.9	0.35	4,470	0.884	5,060	6,980	72	12	21.2	0.35	3,890	0.87
Douglas-fir (Coast)	Bull. 88	10	30.8	0.44	5,440	--	--	--	--	10	16.4	0.46	6,740	1.24
Average of beam and stringer groups (excluding Douglas-fir, Bull. 88)									80					1.12

1/ Wood, L. W. 1947--see footnote 5 of text.
2/ Sources of data are identified more completely--see footnote 5 of text.
3/ Depth factor computed from formula on page 153 of Wood Handbook (1940 edition), using average nominal depths for the various groups.
4/ Based on ovendry weight and ovendry volume.
5/ Includes nearly half beams and stringers, 6 by 12 inches.
6/ Includes nearly half joists and planks, 4 by 10 inches.

given by Newlin and Johnson[4] and was, therefore, more difficult to implement in practice.

By the early 1950's there was an increasing trend to market 2-inch lumber separately from other thicknesses of Joist and Plank. It therefore appeared logical to question whether the 25 percent rule developed for 2- to 4-inch-thick lumber could be liberalized for 2-inch-thick material. After a review of U.S. and unpublished Canadian data (some of which has since been presented (20)) for lumber 1 and 2 inches thick (see table 4), Lyman Wood concluded that basic stresses for green material having a strength ratio of 50 percent or better could be increased by one-fourth if used under continuously dry conditions. This adjustment was judged to be "conservative enough" for most species.[6] As with his previous review, Wood's judgments were apparently based on trends in average strength of lumber in structural sizes.

Standard D 245-57T (1) retained the D 245-49T (1) statement for lumber 2 to 4 inches thick, but noted that "working stresses for all grades of 1- or 2-inch (nominal) lumber that is dressed at 15 percent or lower moisture content and is fabricated and used under conditions where that moisture content is not exceeded, may be increased . . . by one quarter in bending . . ." Note that this latter increase did not depend upon the grade of the material as did the increase given by the 25 percent rule.

Standard D 245-64T (1) retained the 25 percent rule for lumber 2 to 4 inches in nominal thickness and the grade-independent 25 percent increase for 1- to 2-inch nominal thickness lumber surfaced and used at 15 percent or less moisture content. However, an allowable increase in working stress of 15 percent for 1- and 2-inch nominal thickness lumber was added for material at a moisture content of not more than 19 percent at time of manufacture and used under continuous dry conditions.

The 1969 revision of D 245 (1) contained no provision for a moisture adjustment based on strength ratio. In place of this adjustment, a 35 percent increase was allowed for material 4 inches and less in thickness if at a maximum moisture content of 15 percent at time of manufacture and in use; if 19 percent, the allowable increase was 25 percent, provided that the proper allowances were made for shrinkage, table 5. Here it was assumed that lots of lumber dried to a maximum moisture content of 19 percent have an average moisture content of 15 percent and that lots at 15 percent maximum moisture content have an average moisture content of 12 percent. This statement is qualified by the statement that "the increases in allowable properties given . . . at 15 percent

[6] Memorandum from L. W. Wood to R.P.A. Johnson entitled "Increase of Strength with Drying of 2-Inch Lumber." 1953. From the unpublished records of the Forest Products Laboratory.

Table 4.--Ratio of dry[a] to green bending strength (20)

Species	Mean MOR		95 percent tolerance limit of MOR		Nonparameter point estimate of 5th percentile of MOR		Mean MOE	
	2 by 10 joist	2 by 2 clear	2 by 10 joist	2 by 2 clear	2 by 10 joist	2 by 2 clear	2 by 10 joist	2 by 2 clear
Red pine	1.37	1.93	1.29	1.86	1.14	2.09	1.23	1.33
Jack pine	1.33	1.68	0.75	1.46	1.22	1.55	1.28	1.35
White spruce	1.54	1.82	--	--	1.61	1.76	1.31	1.34
Balsam fir	1.48	1.73	--	--	1.88	1.55	1.21	1.28
White pine	1.42	1.82	0.88	1.61	1.09	1.76	1.25	1.28
Eastern hemlock	1.11	1.45	--	--	1.33	1.70	1.23	1.24

a/ Average dry moisture content is 12 to 13 percent.

Table 5.--Modification of allowable unit stresses for seasoning effects for lumber 4 inches and less in nominal thickness, D 245-69 (1)

Property	Percentage increase in allowable stress and modulus of elasticity above that of green lumber when maximum moisture content[a/]	
	19 percent	15 percent
Extreme fiber in bending	25	35
Tension parallel to grain	25	35
Horizontal shear	8	13
Compression perpendicular to grain[b/]	50	50
Compression parallel to grain	50	75
Modulus of elasticity	14	20

a/ The increase for 15 percent maximum moisture content shall not exceed the ratio of dry to green clear wood strength shown in the "Ratios of Dry to Green Clear Wood Properties" included in Methods D 2555 (1). Where ratios in D 2555 are less than above, proportionate reductions shall be made for lumber at 19 percent maximum moisture content.

b/ The increase in compression perpendicular to grain is the same for all degrees of seasoning below fiber saturation since the outer fibers which season rapidly have the greatest effect on this strength property regardless of the extent of the seasoning of the inner fibers.

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maximum moisture content shall not exceed the ratio of dry to green clear wood strength shown in . . . D 2555. When ratios in D 2555 are less than above, proportionate reductions shall be made for lumber at 19 percent maximum moisture content." This statement appears to be the first time that small, clear, dry-green strength ratios have been introduced as a limiting factor for adjusting lumber strength. For most species and properties, the small, clear, dry-green property ratio exceeds the adjustment based on experimental results with lumber. This is the adjustment procedure given in D 245-74 (1), the current edition of the standard.

ASTM standard D 2915-74 (3) contains an equation for adjusting lumber strength properties for changes in moisture content which were formulated to yield the 25 and 35 percent adjustments given in D 245-74 (1). The "assumed" intersection point moisture content, M_p,[7] in this equation varies slightly with the property being calculated. For modulus of rupture (MOR) the assumed value of M_p is 22.5 percent.

Modulus of Elasticity

Early discussions of the effect of seasoning on the flexural properties of dimension lumber did not recognize any increase in the modulus of elasticity (MOE) due to seasoning. The 1956 revision to D 245 (1) made provisions for a 10 percent increase in MOE for 2- to 4-inch nominal thickness lumber that was "continuously dry." For 1- and 2-inch nominal thickness lumber dressed and used at a moisture content of 15 percent or less, the allowable increase due to seasoning was 20 percent. This increase for 1- and 2-inch-thick lumber took the place of the 10 percent increase for 2- to 4-inch-thick lumber used in dry conditions.

In the 1964 revision (1) an increase of 10 percent was still allowed for 2- and 4-inch nominal thickness lumber in dry conditions, but the allowable increase for 1- to 2-inch nominal thickness lumber was further modified. For 1- to 2-inch material dressed and used at a moisture content of 15 percent or less, the allowable increase was raised to 20 percent. For 1- to 2-inch lumber at 19 percent maximum moisture content and used in continuously dry conditions, an increase in working stress of 14 percent was now allowed. The possibility of taking a 30 percent increase for 2-inch-thick lumber used in a dry location was apparently an oversight by ASTM subcommittee D 07.01 arising as a result of many revisions of D 245. The subcommittees possessed no evidence to support addition of the 10 and 20 percent factors.[8]

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[7] The intersection point moisture content is not explicitly given in D 2915-74 but it is that moisture content that causes the denominator of equation (2) of D 2915-74 to be equal to one.

[8] Ethington, R. L. 1980. Personal communication.

Standard D 245-69T (1) extended the 20 percent increase for lots of lumber manufactured and used at a maximum moisture content of 15 percent, and the 14 percent increase for lots of lumber with a maximum moisture content of 19 percent to all lumber 4 inches and less in thickness, table 5. These are the adjustment factors currently given in D 245-74 (1). For lumber greater than 4 inches in thickness, a 2 percent increase in MOE based on the net size at the time of manufacture was allowed, providing the lumber was seasoned to a "substantial" depth before full load was applied.

Tensile, Compressive and Shear Strength

Tension and Compression.--Even though Bulletin No. 108 (5) contained test results for full sized timbers tested in compression parallel to the grain, as well as in bending and compression perpendicular to the grain, no mention was made of seasoning adjustments for compression in ASTM standards until 1949. Standard D 245-49T (1) indicated that the 25 percent rule was also applicable for lumber 4 inches or less in thickness and stressed in compression parallel to the grain. Although the basis for this recommendation is not apparent, Wood[5] observed that such a procedure would yield conservative results for structural size timbers of most species (Wood also observed little correlation between compressive strength and strength ratio). As noted for MOR, it was commercial practice at that time to take advantage of allowable seasoning modifications by liberalizing the single defects allowed in the grade rather than increasing the working stress.

In 1957 the use of the 25 percent rule was extended to lumber 2 to 4 inches in thickness and stressed in tension parallel to the grain D 245-57T (1). Although justification for linking tensile and bending strength adjustments is not apparent, it is consistent with the practice at that time of equating tensile and flexural properties.

For lumber 1 to 2 inches in thickness which was manufactured and used at a moisture content of not more than 15 percent, D 245-57T (1) allowed working stresses in compression parallel to the grain to be increased 37.5 percent over those for green lumber.

Standard D 245-64T (1) retained all the provisions of D 245-57T but added an adjustment for 1- and 2-inch-thick lumber manufactured and used at a maximum moisture content of 19 percent. For compression parallel to the grain the allowable increase over the green strength was 22 percent.

The strength ratio independent adjustments for moisture content currently used for tension and compression parallel, table 5, were first introduced in D 245-69 (1). For the first time, adjustment factors were also given for compression perpendicular to the grain. As in the previous standard, moisture adjustments in tension parallel to the grain were assumed to be equal to those in bending. As noted in the footnote to table 5, provisions were also made for slight increases in compressive strength parallel to grain, and MOE for lumber thicker than 4 inches in certain situations.

Shear.--Prior to 1949 there was only one allowable shear strength for all moisture conditions. However, in the grading process a larger amount of shake was permitted for dry lumber than for green (8). Shear strength was assumed to increase enough upon drying to offset the possibility that shake would lengthen. In D 245-49T (1) there appears for the first time two separate strength ratio tables for shear; one for green lumber and one for dry lumber. The strength ratios for green lumber are the same as those previously used for all moisture contents and are apparently based on tests of small, clear specimens.[9] The strength ratios for dry lumber are 9/8 (13 pct) of those for green lumber.

Standard D 245-57T (1) states that the 13 percent adjustment applies to 1- and 2-inch-thick lumber with a maximum moisture content of 15 percent. In D 245-64T (1) an 8 percent adjustment is added for 1- and 2-inch-thick lumber with a maximum moisture content of 19 percent. These are the adjustments currently given in D 245-74 (1).

STANDARDIZED PROCEDURES IN LIGHT OF RECENT RESEARCH

From the preceding discussion, it is apparent that past and current procedures for adjusting lumber bending strength and stiffness for seasoning effects are based on results obtained from tests of full-size commercial lumber. Also, it appears that the current D 245-74 (1) adjustment procedures are based on changes in average strength properties of full-size lumber which were considered to be "conservative enough" for most species.[6] Current design values, derived from D 245, are

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[9]This judgment by the current author is based on a comparison of small, clear results for shear given in reference (34) and the tables given in D 245-49T (1).

designed to fit a deterministic format based on the 5th percentile. Standard D 245 accomplishes this by the use of clear wood 5th percentiles for strength which are then modified by factors judged by ASTM subcommittee D 07.01 to be adequate for this purpose. From the comments of Newlin and Johnson,[4] Wilson (33), and Wood,[5] there is a suggestion that the magnitude of the moisture adjustment may be dependent upon the strength of the lumber and that adjustments should be based upon near minimum strength rather than the average. Recent research results can be used to investigate this hypothesis.

Modulus of Rupture

Recently, Gerhards (12,13) investigated the effect of seasoning on the flexural properties of 4-inch-thick southern pine conditioned to an equilibrium moisture content of 12 percent. His work indicates that the ratio of dry strength to green strength is dependent upon material quality.

Strength Ratio	Ratio of Dry Strength to Green Strength
28	1.00
50	1.16
76	1.34
100	1.52

Like the initial results reported by Newlin and Johnson[4] Gerhard's dry-green ratios are based on the average properties of the material tested.

In 1971, Jessome (20) reviewed a number of previously unpublished Canadian studies on the bending strength of lumber in structural sizes. The average increase in MOR from green to air dry was found to be about 35 percent. As previously noted, this is some of the same data reviewed by Wood in 1947.[5] Unlike previous investigators, Jessome also calculated the 5th percentile strength of the various species groups. From the calculations of the nonparametric 95 percent tolerance limit with 95 percent confidence, Jessome concluded that "the net effect of drying can be a decrease in strength for full-size specimens" (table 4).

The effect of seasoning on the distribution of strength properties was investigated by Madsen (24) for Douglas-fir 2 by 6, No. 2 and Better, joists (table 6). The 500 pieces selected for this study were randomly assigned

Table 6.--Effect of drying on the modulus of rupture of Douglas-fir joists[a/]

Percentile level	Percent increase due to drying to a moisture content of[b/]				
	25	20	15	10	7
5	0	12	2	7	7
10	0	4	0	8	4
15	0	5	-2	9	9
20	0	3	-5	8	3
25	0	4	2	7	1
30	0	4	7	12	9
40	0	7	11	14	13
50	0	9	8	11	16
75	0	5	11	31	32
90	0	12	17	36	56

a/ Extracted from Table 1 of reference (24).

b/ Percent increase = 100 (dry strength-wet strength) ÷ wet strength.

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to 5 target moisture categories (25,20,15,10, and 5 pct). The lumber was then allowed to dry in the laboratory until readings with an electrical resistance moisture meter indicated that the target moisture level had been reached. The lumber was then tested on edge in 1/3 point bending. Madsen concluded that, although there was some increase in MOR due to drying for the higher percentile levels, there was no increase in the proportion of the pieces that failed at stress levels below 4,000 lb/in.^{2}. A stress level of 4,000 lb/in.^{2} corresponded to approximately the 25th percentile of the cumulative distribution function for this lumber.

Thus, Madsen's results and the analytical work of Jessome (20) agree with the observations of Wilson (33) some 40 years earlier.

Results reported by Hoffmeyer for European spruce (18) differ somewhat from those of Madsen (24). In this study low grade (including a substantial number of "rejects") 45- by 145-mm (1.8 by 5.7 in.) joists were tested at equilibrium moisture contents of approximately 13, 22, and 65 percent in 1/3 point bending. Based on the results of these tests (table 7), Hoffmeyer concluded that there is a consistent dependency between bending strength and moisture content throughout the whole range of strength values. At the 5th percentile, the dry-green ratio approached 1.4.

Table 7.--Effect of drying on the distribution of mechanical properties of European spruce joists[1/]

Percentile level	Percent increase due to drying[2/]			
	Bending		Tension parallel	
	MOR	MOE	Strength	Elastic modulus
1	20	16	0	15
5	37	22	0	4
10	36	32	10	17
25	36	31	1	18
50	53	32	6	20
75	67	35	24	14
90	66	30	20	11
95	71	28	18	9
99	94	23	41	14

1/ Adopted from the total, uncorrected value for dry (13 pct) and wet (65 pct) strengths given in Table 4 of reference (18).

2/ Percent increase = 100 (dry property-wet property) ÷ wet property.

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Although the results obtained by Hoffmeyer and Madsen both indicate a dependency between seasoning factor and strength level, the magnitudes of the adjustments obtained differ substantially.

A direct comparison of the effect of drying on bending strength is shown in figure 4. Both the Hoffmeyer and the Madsen curves indicate that high strength lumber is more sensitive to changes in moisture content than is weaker material. This dependence of strength response to seasoning on different strength levels is probably related to the mode of primary failure. It is generally recognized that first failures in the lower strength material are usually tensile failures occurring at edge knots while first failures in clear material are the result of compressive stresses. As will be shown in the next section, compressive strength is much more sensitive to changes in moisture content than is tensile strength. In fact, it is possible that the tensile strength of the low strength material might be reduced upon drying due to the initiation of a large number of drying checks around knots.

The cause of the difference in the magnitude of the drying effect between the Hoffmeyer and Madsen studies is not readily apparent. It could be related to the existence of moisture gradients within the pieces. Hoffmeyer's study

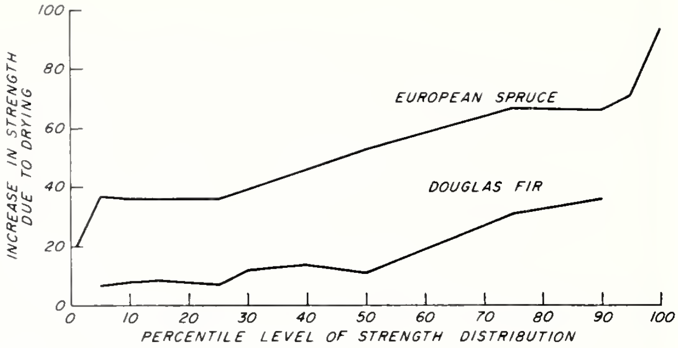

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Figure 4.--Effect of strength level on the increase in bending strength due to drying (18,24).

was conducted at equilibrium moisture conditions, and the Madsen samples were tested while in the process of drying and undoubtedly contained pronounced moisture gradients. Most likely the average (nonequilibrium) moisture content of the Madsen samples was significantly higher than the (equilibrium) moisture content of the surface fibers. Because the strength of the outer fibers has the largest effect on bending strength, the observed MOR probably corresponds to a lower moisture content than the moisture content measured. Results presented by Wilson for 2 by 4's (33) tend to support this thesis, at least for moisture contents below the fiber saturation point (fig. 5). Unfortunately, the Madsen data provide no measure of the magnitude of the moisture gradient.

A problem usually encountered in deriving analytical expressions for describing the moisture content-strength relationship is to accurately establish the threshold moisture content at which property changes due to drying are first observed; the M_p value defined by Wilson (33). Underestimation of M_p will decrease the estimated strength response to changes in moisture content. In his study of Douglas-fir Madsen (24) assumed that pieces which had a moisture meter reading of 25 percent were "wet", $M_p = 25$, and based his dry-green ratios on the strength of these pieces. Hoffmeyer (18) obtained his moisture contents from ovendry measurements, the minimum value of which was 38 percent (the average was 65 pct). Thus, the difference between the results obtained in the Madsen and Hoffmeyer studies could be a result of Madsen's assumption that lumber having a moisture content of 25 percent was "green."

Differences in sorting and grading practices used in selecting lumber for the two

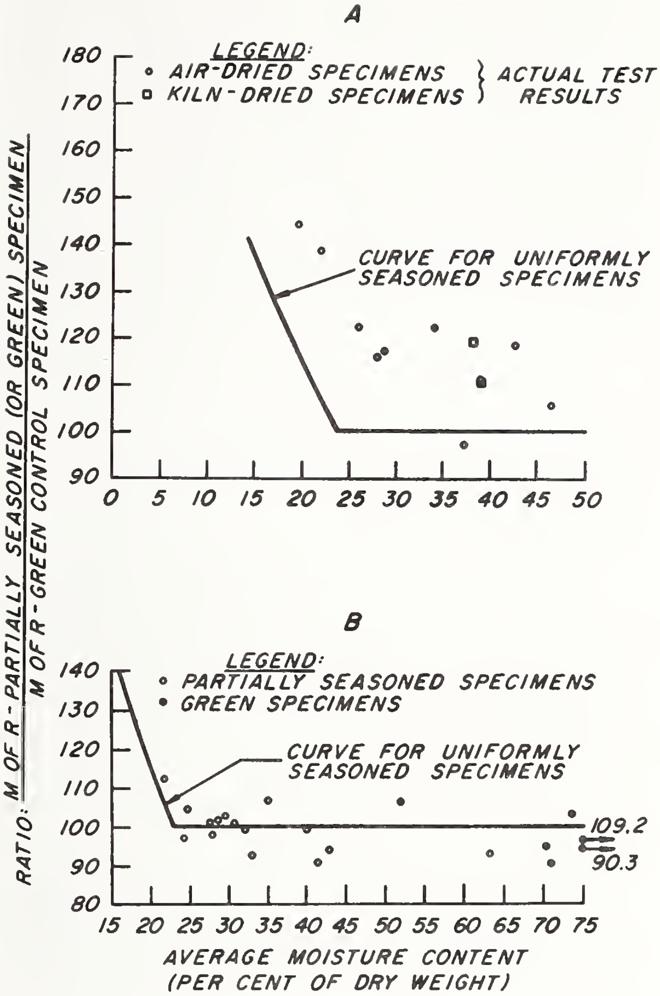

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Figure 5.--Effect of partial seasoning on the modulus of rupture of 2 by 4 lumber (33).

studies, or anatomical differences between the two species used could also contribute to the difference.

All four reports summarized here agree on one point, the increase in the modulus of rupture for 2-inch-thick lumber depends upon the strength (or estimated strength) level of the material. What is not clear is the magnitude of the adjustment required for different moisture levels and strength ratios, especially for the 5th percentile. The current D 245 adjustment procedure indicates a 35 percent increase in bending strength for lumber 4 inches or less in thickness which is manufactured and used at a maximum moisture content of 15 percent. Madsen's results indicate that for Douglas-fir no adjustment is warranted, while the studies of Hoffmeyer suggest that the current adjustment is satisfactory. Given the tremendous engineering and economic implications of the alternatives, more studies are obviously needed.

Modulus of Elasticity

The quality independent factor for mean MOE given in table 5 is in reasonable agreement with experimental evidence for dimension lumber. For example, Gerhards (12,13) concluded that the average increase in MOE was 23 percent when drying green 4-inch-thick southern pine to an equilibrium moisture content of 12 percent. This agrees with an increase of about 20 percent found by Wood and Soltis (35) for drying several grades and sizes of southern pine, Douglas-fir, and western hemlock to a moisture content of 11 percent.

For tests on Douglas-fir, 2 by 6, No. 2, joists, Madsen (24) observed an increase in the MOE with decreasing moisture content at all stiffness precentiles. He further concluded the increase in stiffness per percentage point decrease in moisture content increased at the lower moisture content levels. This trend is not readily apparent from table 8. From table 8 it also could be concluded that the percentage increase in MOE is less dependent on strength level than is MOR.

Table 8.--Effect of drying on the modulus of elasticity of Douglas-fir joists[a]

Percentile level	Percent increase due to drying to a moisture content of[b]			
	25	15	10	7
5	0	10	6	15
10	0	10	6	17
25	0	2	6	13
50	0	7	5	20
75	0	8	10	23
90	0	11	8	24
95	0	11	11	21

a/ Extracted from Table 2 of reference (24).

b/ Percent increase = 100 (dry strength-wet strength) ÷ wet strength.

More recently, Madsen and Nielsen (25) studied the effect of seasoning on the MOE of several sizes of No. 2 and Better Hem-fir. They found that the seasoning factor for drying lumber from an assumed fiber saturation point of 40 percent to a moisture content of 12 percent was smaller than that given in D 245-74 and concluded that the ASTM corrections are not suitable for lumber. However, an electrical-resistance moisture meter was again used to obtain the moisture content of the lumber, and this type of meter is known to give unreliable results above a moisture content of about 30 percent (32). Madsen and Nielsen note, "It should be mentioned that our total adjustment from the green condition to 12 percent moisture content might well be as big as that given by the other formulas (including D 245-74) due to the fact that the correction in some cases is done from 40 percent, rather than from 25 percent moisture content."

The results obtained by Hoffmeyer (18) (table 7) also indicate that the effect of drying on MOE is less dependent upon percentile level than is MOR. Again, the magnitude of the seasoning increase is greater for the Hoffmeyer tests than for the Madsen-Nielsen tests.

The results obtained by Jessome (20) are intermediate in magnitude between those of Madsen and Hoffmeyer but sustain the hypothesis of little dependence between MOE and strength level.

Stiffness and Moment Potential

Since both the MOE and MOR are sensitive to changes in moisture content, design procedures could be simplified if alternative parameters could be measured which were relatively insensitive to changes in moisture content. Two alternative parameters which have been considered are stiffness (EI) and moment potential (RS).

For a constant span, the ability of a beam to resist deflection is indicated by the product of the MOE and the moment of inertia (I). Since the MOE increases and the I decreases as wood dries, it might be anticipated that the stiffness would be constant. In fact, several studies have shown that "on the average" EI changes but little as the beam dries. Hoyle[10] investigated the effect of drying (green to 12 pct average moisture content) on the stiffness of several sizes of Douglas-fir and white fir lumber. Increases in the average EI ranged from 3 to 12 percent. However, variability was quite high and a few negative changes were reported (negative changes indicate the effect on I may exceed that in MOE). Johnson (21) found the ratio of dry-to-green EI to be from 1.00 to 1.06 for Douglas-fir 2 by 6's. Wood and Soltis (35) concluded that dry-green ratios varied little with moisture content. Covington and Fewell (6) found that the ratio for Canadian hemlock increased slightly upon drying.

The load that a beam can support at constant span depends upon RS, the moment potential of the member. RS is defined as the product of the MOR and the section modulus (S). Again, it might be anticipated that MOR increases upon drying while S decreases, leaving RS unchanged.

Few studies have compared RS before and after seasoning. Johnson (21) found the ratio of dry-to-green RS values to range from 1.30 to 1.24 for 2 by 6 Douglas-fir joists. No indication of the interaction between RS and strength level was given.

Tensile and Compressive Properties Parallel to the Grain

Tensile properties.--The evolution of tensile design stresses for lumber has recently been reviewed by Galligan, et al. (10). However, none of the studies cited in this review focused on the strength-moisture relationship.

Hoffmeyer (18) studied the influence of moisture content on the tensile properties in his evaluations of European spruce. As in the bending studies previously cited, the effect of moisture content on tensile strength was found to depend upon strength level. Below about 2,200 lb/in.^{2} seasoning did not influence tensile strength (table 7). For the higher strength lumber there was a significant difference between green and dry lumber. Hoffmeyer cautions, however, that there was some warping of the tensile specimens during drying which may have caused premature failure. As with MOE, the tensile elastic modulus is less dependent upon strength levels than is tensile strength.

Madsen and Nielsen (27) used the dry-out procedure to investigate the effect of moisture content on tensile strength using 2 by 6, No. 2 and Better Hem-fir. Below about 3,000 lb/in.^{2} (30th percentile) tensile strength was found to be independent of moisture content (fig. 6).

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[10]Hoyle, R. J. 1962. A study of the relationship between moisture content and strength and stiffness of Douglas-fir and white fir, personal communication.

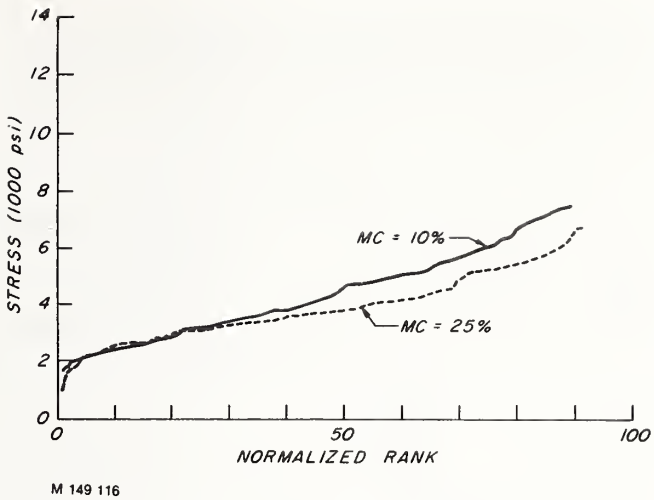

Figure 6.--Effect of moisture content on tensile strength parallel to the grain (27).

At the 50th percentile, the increase due to seasoning is somewhat less than that permitted by D 245-74 (1).

Compressive properties.--The effect of moisture content on compressive strength differs somewhat from that in flexure and tension. For Hem-fir 2 by 4's, Littleford and Abbott (23) concluded that moisture content appears to influence the total distribution. The mean ratio of dry (12 pct) to green strength was approximately 2 and varied but little with strength level (fig. 7). Studies by Hoffmeyer (19) confirm the observation of Littleford and Abbott. For European spruce Hoffmeyer obtained a ratio of dry-to-green strength of about 2.5.

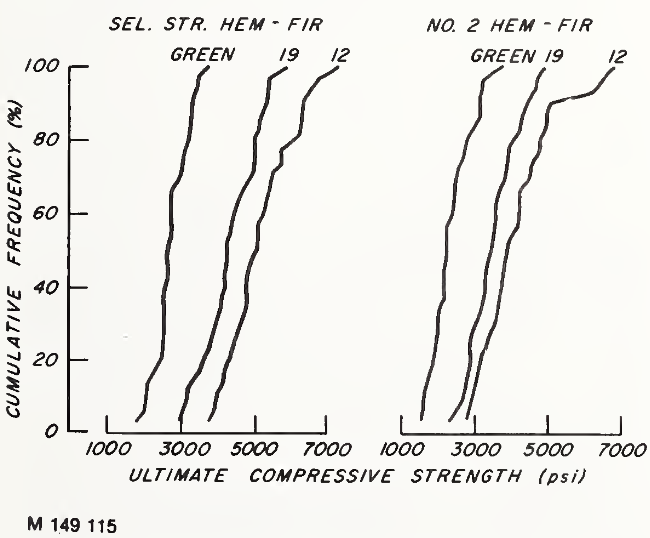

Figure 7.--Cumulative frequency distributions for ultimate compressive strength of Select Structural and No. 2 grades of 2- by 4-inch Hem-fir at 12 percent, 19 percent, and green moisture conditions (23).

As in bending, the effect of moisture content on the compressive elastic modulus is approximately independent of moisture content. Hoffmeyer (18) obtained a dry-green ratio for compressive modulus of approximately 1.4 (fig. 8).

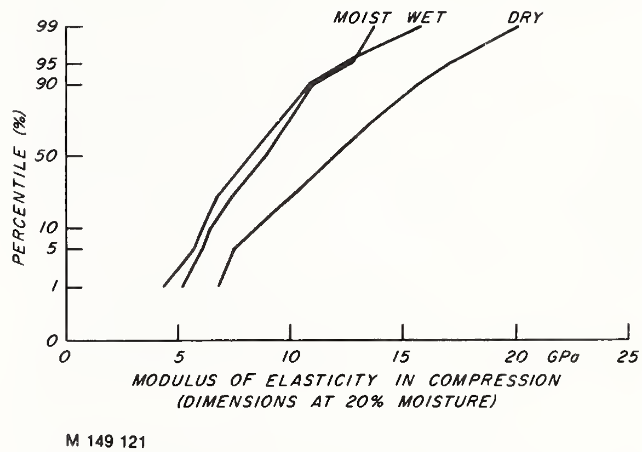

Figure 8.--Distribution functions for corrected modulus of elasticity in compression at moisture content levels 15.2, 21.4, and >29 percent (18).

RESEARCH IMPLICATIONS OF THE STRENGTH-MOISTURE CONTENT RELATIONSHIP

Assessing the Importance of the Strength-Moisture Content Relationship

Structural simulation studies.--Left on his own, the material scientist may tend to try to establish the strength-moisture content relationship with a degree of precision greater than is appropriate for the intended use. To provide input to such an effort, it may be necessary to cooperate with a structural engineer to conduct computer simulation studies of the effect of a change in material properties on structural system performance. Obviously, if the simulations indicated that structural performance will not be affected by substituting green lumber for dry, then the material scientist must reconsider the need for breaking the large number of boards required to accurately assess the strength-moisture relationship.

For structural systems where load sharing may be important, it may not be easy to speculate on the sensitivity of structural system performance to changes in moisture content. One might speculate that the structural performance of a light frame floor system with a high degree of load sharing might be less sensitive to changes in the moisture content of the joists than a wall system in which there was little load sharing. In order to obtain

some preliminary information, simulations of wall and floor system performance for varying moisture adjustment procedures are being conducted by Oregon State University, Colorado State University, and the U.S. Forest Products Laboratory as part of the In-Grade Testing program (11). The results of these studies should be available in the near future.

The effect of a change in moisture content on truss performance is also an important consideration. The discussion in the previous section suggests that changes in the moisture content of lumber affect compressive, bending and tensile strength to varying degrees. By the use of computer simulation, it should be possible to quantify truss performance relative to current design practice and to use this information to estimate the importance of a moisture-induced change in lumber properties. This procedure could also be used to estimate the potential impact of a proposed change in design procedures.

Reliability analysis.--Structural engineers are becoming increasingly interested in the use of probabilistic methods in structural design (9,36). Probabilistic methods are increasingly being used to estimate the sensitivity of product performance to variations in material performance (28,31). The probability of failure, P_f, is traditionally calculated as (31),

$$P_f = \int_{-\infty}^{\infty} [\int_{-\infty}^{S} F_R(r)dr]F_S(s)ds \qquad (3)$$

where

$F_R(r)$ = the probability density function of resistance, and
$F_S(s)$ = the probability density function of load.

Figure 9 illustrates the physical implications of equation (3).

This technique can be used to evaluate the need for further analysis of the strength-moisture content relationship. Suppose that you had a good data set for lumber at a high moisture content and a little information on lumber properties at a low moisture content. In order to calculate probability of failure, it will be necessary to superimpose an assumed load distribution on the probability density function for the dry lumber and calculate the probability of failure using equation (3). Then superimpose the same load distribution on the distribution for the wetter lumber, repeat the calculation and compare the probabilities of failure. A reasonable adjustment factor for use with current design procedures might be obtained by requiring equal probabilities of failure for the green and dry distributions.

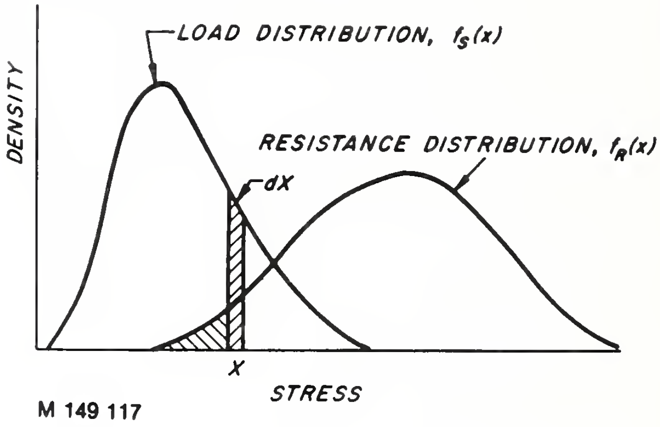

Figure 9.--Representation of probability of failure. The product of shaded areas is an increment element of probability of failure. The total of such products for all possible values of x is the probability of failure for the prescribed load and resistance distributions (adopted from reference (31)).

As an example, consider that the probability density functions are described by the Weibull parameters,

Moisture content	Weibull parameters			
	Shape	Scale	Location	5th percentile
	- - - - - 10^3 lb/in.^{2} - - - - - -			
Wet	2.586	4.309	0.903	2.269
Dry	1.845	4.597	1.304	2.223

In current deterministic design the 5th percentile is the parameter of interest. In the example given above, the ratio of the 5th percentile for the dry lumber to that of the green lumber is 0.98. Assuming that the load may be described by a Gumbel type I, extreme value distribution and setting the 95th percentile of the load distribution equal to the 5th percentile of the respective material property distribution, the probabilities of failure may be calculated. In this example, the probability of failure of the dry lumber is approximately equal to that for the green lumber. If, however, the 95th percentile of the load distribution were equated to a lower percentile level of the material strength distribution, the difference in the probability of failure of the

dry lumber and that of the green lumber might be dramatically changed (table 9).

Table 9.--Effect of drying on the probability of failure, P_f

Ratio of load (95th percentile) to resistance (5th percentile)	P_f for dry lumber ÷ P_f green lumber
1	1.00
3/4	1.20
1/2	1.30
1/4	1.34

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The calculations shown were only given to illustrate the application of the technique in assessing the potential input of additional properties research on product performance. Many other factors might need to be considered in selecting load and resistance distributions; some of which are discussed by Suddarth, et al. (31). The example illustrates that additional properties research may not improve product performance unless realistic load information is also available. Note also that this technique provides an alternate method for assessing the significance of a difference in results from two independent studies.

Single member properties.--When trying to assess the relative importance of moisture content on the strength of wooden structural members which will be designed as individual units, it may be somewhat easier to determine the required precision. In designing an experiment to look at the effect of equilibrium moisture content on the flexural properties of laminated beams our current knowledge suggests that moisture content could significantly affect the test results. From the previous discussion it is apparent that high strength (quality) lumber would be more sensitive to changes in moisture content than would low strength (quality) lumber. Thus, if one were conducting a study of the properties of tension laminations for use in a study to predict the properties of laminated beams, it might be more important to obtain adequate conditioning of the samples than if one were testing utility grade dimension lumber in an in-grade testing program.

From the discussion in the previous sections, it is apparent that the effect of a change in moisture content on lumber strength distributions is still open to question. While it would be desirable to have resistance distributions for all grade/size combinations of all major structural species at several moisture conditions, such information would be extremely expensive to obtain by sampling and testing and does not represent a practical research goal. Alternatively, an analytical model could be developed to predict the strength-moisture relationship for the grade-size matrix of major species. Such a model would be useful for both deterministic and probabilistic design procedures and, hopefully, could be used to predict the behavior of lumber even if there are future changes in lumber grading procedures.

To quantify the effect of moisture content on the flexural properties of Southern Pine and Douglas Fir dimension lumber, a cooperative research program has been initiated between the U.S. Forest Products Laboratory, Forintek Canada Corp. (Western Forest Products Laboratory), and Virginia Tech. The objective of this program is to develop an analytical model to adjust flexural properties for end-use moisture conditions. Each of the two studies in progress is composed of approximately 3,600 pieces of lumber in three grades (No. 3, No. 2, and Select Structural) and three sizes (2 by 4, 2 by 6, and 2 by 10). Approximately 100 pieces of lumber for each grade/size category will be conditioned to equilibrium moisture contents of 10, 15, and 20 percent and also tested green. Further details of the experimental design are given in the presentation by DeBonis (7).

While studies on flexural properties are already in progress, additional work is required for other modes of loading. Tensile and compressive strength should be investigated for an additional major softwood species. Consideration should also be given to evaluating the effect of moisture content on other species--especially a small knotted softwood species and a structural hardwood species. The significant anatomical differences between hardwoods and softwoods and the lack of previous work on strength-moisture relationship for hardwoods make this study particularly important. It may be sufficient at present to conduct a sensitivity study to compare the strength-moisture relationship for these species with the results being established for the major species. Given the significant effect of moisture content on compressive strength and stiffness parallel to the grain, it would appear desirable to investigate the effect of moisture content on the structural performance of short, intermediate, and long columns.

The effect of various sawing practices on moisture content-strength properties is not readily apparent. For example, the behavior of lumber produced from peeler core stock might be different than that of lumber sawn more conventionally.

Additional Research Considerations

Nonidealized environments.--Lumber in use may be subjected to a number of nonidealized conditions that deserve further investigation. One such condition, the existence of nonequilibrium moisture gradients, has already been mentioned. It is generally acknowledged that lumber fresh from the kiln may contain severe moisture gradients. In order to adjust strength for changes in moisture content, it is first necessary to measure the actual moisture content. The usual instrument used to measure moisture content in the field is the electrical resistance moisture meter. The effects of the magnitude, form, and distribution of these gradients on moisture meter calibration procedures must be quantified if strength adjusting models are to be used effectively. In addition, high temperature drying may reduce strength and stiffness or reduce hygroscopy. Such effects need to be evaluated. Studies of this nature have been recommended by ASTM subcommittee D 07.11 and are being pursued in cooperative studies between the U.S. Forest Products Laboratory, Louisiana State University, and the University of California at Berkley.

In use, lumber is often subjected to varying climatic conditions. It is well established that the deflection of a small, defect free beam when loaded and subjected to a cyclic moisture content will creep significantly more than expected based on results obtained from static moisture conditions (17). The probability of creep rupture is increased by such conditions. This phenomenon has been studied using clear wood but has not been thoroughly investigated for structural-size members of varying sizes and grades. Establishment of creep rupture effects under cyclic environmental conditions for structural lumber thus should be of particular importance in engineering research. A more detailed discussion of this phenomenon is given in the presentation by Gerhards (15).

SUMMARY AND CONCLUSIONS

Traditionally, moisture content has been considered to be one of the most important environmental factors affecting the strength of lumber. Based on tests of full-size commercial lumber conducted by the Forest Service prior to 1924, an analytic expression was developed for describing the influence of moisture content on flexural working stresses. This expression was included in ASTM Standard D 245 from 1930 until 1969. The magnitude of this adjustment was dependent upon the thickness of the piece and the minimum strength ratio. Current adjustment procedures in D 245 are independent of the quality of the lumber and are apparently based on results of structural tests. These adjustments reflect mean strength-moisture effects which were judged by committee to be conservative for design with most species.

Adjustment procedures for other properties were not originally given in D 245 but were added after 1948. Adjustment procedures for tension parallel to the grain have traditionally been equated to those used for bending. Adjustment procedures for MOE and compressive strength parallel to the grain were apparently established from test results for full-size lumber. Adjustments of shear strength for moisture content were apparently based on test results obtained using small, clear specimens. As with bending, current adjustment procedures for other loading modes are independent of lumber quality.

A review of current literature supports the contention that the moisture content adjustment procedure for bending and tensile strength should depend upon the thickness and quality level (strength ratio) of the lumber. Given the conflicting results that exist in the literature, it is not readily apparent what the magnitude of the adjustment should be. The literature suggests that for design purposes it may be sufficient to assume a constant percentage adjustment for modulus of elasticity and compressive strength parallel to the grain. It is also apparent that the adjustment procedure for tensile strength parallel to the grain may not be the same as that for bending strength at all percentile levels.

The following items, listed in order of general overall priority, are suggested for future research consideration.

1. Distributional based analytical models must be developed for predicting the strength and stiffness of lumber at different moisture contents.

2. Simulation and reliability studies should be conducted in order to determine the potential impact of a change in the moisture adjustment procedures on the design process and to provide insight on the need for additional research in specific areas.

3. Studies should be initiated to determine the significance of cyclic environmental conditions on lumber strength and stiffness.

4. After adjustment procedures have been established for major structural species, additional studies should be initiated to confirm these procedures for other lumber species, especially for hardwood species approved for structural use.

5. The effect of specific drying methods and realistic moisture gradients on the strength-moisture relationship should be evaluated.

6. Studies should be initiated to determine the effect of moisture content on the performance of short, intermediate and long columns.

In anticipation of future changes in the design process, these studies should result in information relevant to a distribution of strength properties. In view of the potentially greater effect of moisture content on high quality lumber, research emphasis should focus on the higher grades of visually and mechanically graded lumber used in highly engineered structures.

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STRENGTH-MOISTURE CONTENT RELATIONSHIPS FOR SOUTHERN PINE STRUCTURAL LUMBER: A PROGRESS REPORT[1]

by

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ABSTRACT

The effect of moisture content on the strength and stiffness of southern pine dimension lumber is being investigated. Three visual grades (Select Structural, No. 2 and No. 3) and three sizes (2x4, 2x6 and 2x8) are being conditioned to four target moisture content conditions (10%, 15%, 20% and green). The lumber is being non-destructively evaluated in a flatwise orientation for determination of Modulus of Elasticity (MOE) and is then tested to failure in edgewise bending to evaluate MOE and Modulus of Rupture (MOR). It is anticipated that the relationships found will be used for the development of an analytical model describing the effect of moisture content on the strength and stiffness of visually-graded southern pine dimension lumber.

INTRODUCTION

Traditionally, allowable design stresses for visually-graded lumber have been established by using two key ASTM standards. First, clear wood strength properties for various species are determined according to the methods outlined in ASTM D-2555, "Standard Methods for Establishing Clear Wood Strength Values" (1979). Following this, adjustment of these properties for various visual grade characteristics are made using ASTM D-245, "Standard Methods for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber" (1979). These adjustments include such factors as those for duration of load, strength ratio, and moisture content.

Recent investigations, however, indicate that discrepancies may exist in some cases between the strength and stiffness values obtained by traditional methods and the strength and stiffness values obtained for visually-graded dimension lumber tested in flexure (Madsen 1975a; Bodig 1977). In addition, the traditional method for establishing allowable stresses has recently come under criticism (Madsen 1975a). For these reasons, both the United States (Galligan and Haskell 1979) and Canada (Madsen 1977) have undertaken major research efforts commonly referred to as In-Grade Testing programs. Within the scope of these programs, various species, grades and sizes of visually-graded dimension lumber are tested at mill locations in an effort to evaluate the bending strength and stiffness of this material.

It is important to evaluate not only the structural properties of this material, but also the effects of some of the primary factors

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that influence these properties. The influence of moisture content is one such factor which may have a significant effect on the strength and stiffness of visually-graded dimension lumber. Currently, modifications of allowable stresses for moisture content have been grade-independent. However, recent investigations have indicated that although this may be true for stiffness, the effect of seasoning on strength of dimension lumber may be dependent on material quality (Gerhards 1968, 1970; Madsen 1975b).

The objective of this study is to investigate the effect of moisture content on the flexural properties of southern pine dimension lumber and to develop analytical models for adjusting lumber strength and stiffness data for end-use moisture conditions. In addition, a complementary study with western species is presently being conducted as a cooperative research effort between the U. S. Forest Products Laboratory and Forintek Canada Corporation.

LUMBER SAMPLING

Due to the large variation associated with strength and stiffness of visually-graded dimension lumber, it was felt that relatively large sample sizes were needed to determine the response of these properties to moisture content changes. The target lumber sampling plan is illustrated in Table 1. As can be seen from this table, three grades (Select Structural, No. 2 and No. 3), three sizes (2x4, 2x6 and 2x8) and four target moisture content groups (10%, 15%, 20% and green) were considered.

Since the material was to be selected in the rough, green state, it was necessary to make adjustments in the number of samples taken for each grade and size for two purposes: 1) to include additional samples for expected degrade due to seasoning and 2) to include additional samples for expected up-grade or down-grade due to surfacing. This proved to be at best an educated guess and will contribute to deviations from the original target sample sizes.

All rough, green material was selected from the green chain of a high-production sawmill in the Tidewater region of Virginia by a Southern Pine Inspection Bureau (SPIB) Quality Supervisor. After all material was selected, it was planed to SPIB standard rough, green sizes (1979), sprayed with a fungicide, and re-graded. During the re-grading operation, the maximum strength-reducing defect and the grade-controlling defect were coded by the SPIB supervisor.

To assess the effect of moisture content, it was felt that the four lumber populations should exhibit similar initial strength and stiffness distributions prior to seasoning. A technique presented by Warren and Madsen (1977) was used in a modified form for this purpose and is presented here as follows:

1) Each piece of lumber was tested on a long span (59.5" for 2x4's; 93.5" for 2x6's and 123.25" for 2x8's) in a flatwise orientation with a mid-span concentrated load applied to determine a relative estimate of board stiffness (relative MOE). The estimate is relative in that the field equipment was not as stiff as its laboratory counterparts. Consequently, the recorded deflection may have had a machine-dependent component. However, this component

Table 1 - Target sample sizes

Moisture Content Group	Size	GRADE Select Structural	No. 2	No. 3	Total
10%	2x4	*	*	*	300
	2x6	*	*	*	300
	2x8	*	*	*	300
15%	2x4	*	*	*	300
	2x6	*	*	*	300
	2x8	*	*	*	300
20%	2x4	*	*	*	300
	2x6	*	*	*	300
	2x8	*	*	*	300
Green	2x4	*	*	*	300
	2x6	*	*	*	300
	2x8	*	*	*	300
Total		1,200	1,200	1,200	3,600

* = 100 specimens

was constant for each lumber size. Since relative deflection within a size of lumber was the key variable to be evaluated, the equipment adequately provided this information.

2) The maximum strength-reducing defect in the middle one-third of the specimen on the tension edge (assuming eventual testing in an edgewise orientation at third points) was assigned a strength ratio (ESR) to provide an estimate of board strength. The tension edge was selected prior to grading in a systematic manner to insure random placement of strength-reducing defects on tension and compression edges for later testing.

3) The estimated stiffness and strength data were recorded along with the specimen number on the back of an IBM computer punch card.

4) When all the lumber was tested, the computer cards were sorted according to the following scheme:

a) Within a size and grade, the cards were sorted in descending order by the relative MOE. The range of stiffness was divided into classes of approximately 200,000 psi for 2x4's and 100,000 psi for 2x6's and 2x8's.

b) Within a size, grade and relative MOE class, the cards were sorted in descending order according to the assigned estimated strength ratio.

c) Within a size and grade, the first card which, in essence, represented the board or one of the boards with the assumed greatest stiffness and strength was placed into one of four groups. The second card was placed in the second group. This process continued until all cards within a size and grade were placed in one of the four groups. This was then repeated for each stiffness class and each grade and size until all specimens were sorted into the four groups. Each of the groups was then assigned a moisture content class (10%, 15%, 20% or green). Following the card sort, a master list was developed for specimen numbers within each of the four moisture content groups by size and grade. The lumber was then placed on a breakdown chain and hand-sorted according to the master list.

Figures 1 and 2 illustrate representative histograms for the relative MOE and estimated strength ratio distributions within the four moisture content groups for the 2x8 lumber. Table 2 provides numerical estimates of means, standard deviations and coefficients of variation for the four moisture content groups sorted by size. It is obvious from Figures 1 and 2 and Table 2 that the method used was extremely satisfactory in developing relatively equivalent strength and stiffness distributions. Table 3 lists summary statistics for the 2x6 lumber sorted by grade. Again, the results suggest that within grades a relatively equivalent representation was achieved.

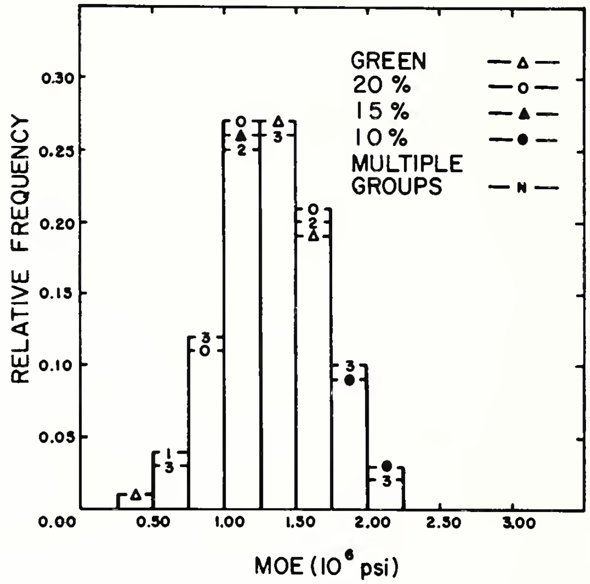

Figure 1 - Histogram of relative MOE for the 2x8 lumber in the four moisture content groups.

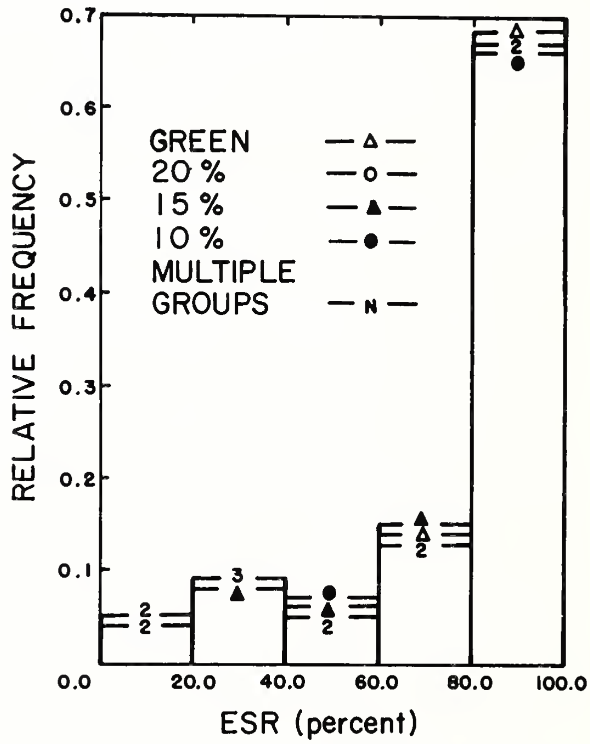

Figure 2 - Histogram of estimated strength ratio for the 2x8 lumber in the four moisture content groups.

Table 2 - Statistical summary for relative flatwise Modulus of Elasticity and estimated strength ratio distribution within the four moisture content groups sorted by size

Size	Moisture Content	Variable	No. of Specimens	Mean[1]	St. Dev.[1]	C. V. (%)
2x4	Green	MOE	327	1.351	0.366	27.09
		ESR	327	77.50	26.11	33.69
	20%	MOE	329	1.353	0.396	29.27
		ESR	329	78.37	25.49	32.53
	15%	MOE	328	1.349	0.369	27.35
		ESR	328	79.08	24.77	31.32
	10%	MOE	327	1.352	0.365	27.00
		ESR	327	78.44	25.89	33.01
2x6	Green	MOE	330	1.449	0.382	26.36
		ESR	330	79.59	23.69	29.77
	20%	MOE	331	1.455	0.372	25.55
		ESR	331	79.50	23.76	29.89
	15%	MOE	330	1.458	0.377	25.85
		ESR	330	79.76	23.05	28.90
	10%	MOE	331	1.458	0.372	25.52
		ESR	331	78.91	24.32	30.83
2x8	Green	MOE	329	1.358	0.354	26.07
		ESR	329	79.14	25.21	31.85
	20%	MOE	329	1.361	0.349	25.64
		ESR	329	78.20	26.15	33.44
	15%	MOE	329	1.360	0.355	26.10
		ESR	329	79.20	24.87	31.40
	10%	MOE	329	1.357	0.345	25.42
		ESR	329	78.23	25.75	32.92

[1] MOE - 10^6 psi
ESR - %

Table 3 - Relative flatwise MOE and ESR for 2x6 lumber - No. 2 grade

Moisture Content	Variable	No. of Specimens	Mean	St. Dev.	C. V.
Green	MOE	121	1.400	0.382	27.25
	ESR	121	74.50	23.37	31.37
20%	MOE	120	1.407	0.376	26.73
	ESR	120	75.05	22.70	30.25
15%	MOE	121	1.399	0.359	25.64
	ESR	121	73.14	23.97	32.78
10%	MOE	124	1.402	0.358	25.57
	ESR	124	73.00	23.62	32.35

LUMBER CONDITIONING

Throughout the sampling procedure it was essential to insure that the lumber did not dry below the fiber-saturation point. For this reason, the lumber was thoroughly sprayed with water whenever it became apparent that the surfaces of the lumber were beginning to dry.

Upon completion of the sorting procedure,

the "green" lumber sample was left in the mill yard for continued wetting. The three "dry" moisture content groups (10%, 15% and 20%) were carefully dried in kilns at the mill site using a mild schedule. The maximum kiln temperature attained was 155°. These groups were removed from the kilns when they were considered to be within several percent above the target moisture contents.

Following the initial seasoning, the lumber was solid piled, load wrapped and shipped by truck to Blacksburg, Virginia. Upon arrival, the lumber was stickered and placed in pre-constructed, temporary conditioning chambers as shown in Figure 3. The chambers contained fans for air circulation and dehumidification or humidification, depending on the desired EMC.

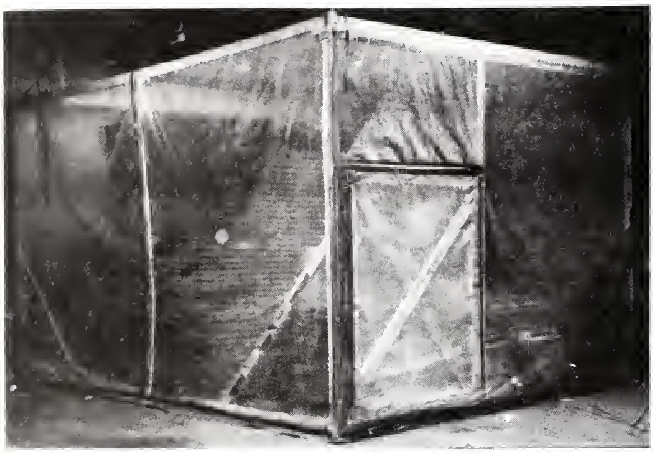

Figure 3 - Temporary conditioning chamber

The lumber will be in the chambers from six to nine months, depending on the target EMC. Since the vast majority of the pieces were initially above the target moisture content, they will be continually desorbed to the target value. Relative humidity and temperature in the conditioning chambers are currently monitored on a continuous basis. Moisture content of the lumber is monitored periodically with a resistance-type moisture meter. At the time of this writing, 204 2x4 specimens from the 20% chamber have been tested to destruction, thus facilitating obtaining ovendry moisture content samples. The average moisture content of these specimens is 18.44%, with a standard deviation of 0.96%.

This indicates that adequate control of temperature and relative humidity has been achieved in the temporary conditioning chambers. Although the moisture content is slightly low for this chamber, the standard deviation indicates equilibrium has been reached.

LUMBER TESTING

Each piece of lumber sampled will be tested in two modes of bending in the laboratory. The first is a flatwise, short-span test for determination of MOE only. This test is entirely within the linear range of the material. The second test is an edgewise bending test to failure for the determination of edgewise MOE and MOR. These two test technqiues are discussed here.

Each day, approximately 30 specimens are removed from the conditioning chambers and brought to the laboratory. Each piece is tested in a flatwise orientation, simply supported, with a single concentrated load applied at the middle of a four-foot span. Deflection at mid-span is measured by a linear potentiometer.

The specimens are then placed in a second testing machine and are oriented on edge according to the prior selection of the tension face. This test machine was built specifically for this study. The edgewise-oriented specimen is simply supported over a span determined by a span/depth (l/d) ratio of 17:1 and is loaded at third points. This l/d ratio was selected consistent with that of the In-Grade Testing Program (Galligan and Haskell 1979). The lateral supports, load heads, and reaction supports were designed according to ASTM D-198, "Static Tests of Timbers in Structural Sizes" (1979). Load is applied by a hydraulic cylinder and is measured with a load cell placed behind the cylinder. Deflections are measured at mid-span and over the reactions with the use of LVDT's. The average reaction deflection is then subtracted from the mid-span deflection for computation of MOE.

One of the principal deviations made from standard procedures outlined in ASTM D-198 (1979) is the rate of cross-head travel used to test the specimens to failure. There are several very specific reasons for this deviation. Considering the excessive amount of material to be tested (approximately 3,600 pieces of dimension lumber) and the suggested ASTM rate which is based on an average time to failure of approximately ten minutes, an estimated 15 working weeks of test time alone would be required to test all of the material. In addition, recent literature suggests that the effect of loading rate on strength appears to be less severe than previously assumed for loading rates causing failure in times less than ten hours, that it may be dependent upon the original strength of the material, and that it acts similarly for both wet and dry materials (Madsen 1975c; Madsen and Barrett 1976; Spencer 1979; DeBonis, Woeste and McLain 1980).

For these reasons, it was decided to test this material more rapidly than the rate suggested in ASTM D-198 (1979). This decision was based on discussions between the authors of this paper and their cooperators at the U. S. Forest Products Laboratory and Forintek Canada Corporation. The rate of cross-head travel to be adopted was to be based on an estimated time to failure of one minute for the weakest 10% of the material under investigation. From limited testing at various rates of cross-head travel of No. 3-grade, green southern pine dimension lumber with limiting maximum defects, this rate was established as 2.0 in./min. This rate was corroborated with similar but independent testing at the U. S. Forest Products Laboratory.

All load and deflection trace data are collected automatically on a MINC-11 mini-computer made by Digital Electronics. The data points and the MOE and MOR are stored on floppy disk and then transferred in bulk to an IBM-370 computer. Figure 4 is a photograph of the equipment used for the edgewise bending tests. Figure 5 illustrates the mini-computer used to monitor the load-deflection curves and store the data. Following completion of the test, moisture content and specific gravity samples are removed from the failed specimens.

Figure 4 - Edgewise bending test apparatus

Figure 5 - Edgewise bending test in progress with load-deflection trace being monitored on a mini-computer.

STATE OF THE PROJECT

At the time of this writing, all of the lumber specimens in the green chamber have been tested to failure. Approximately 200 2x4's in the 20% chamber have been tested. The lumber in the 20% chamber has been regraded by the same SPIB Quality Supervisor who performed the original grading to evaluate degrade due to seasoning. Each of the remaining chambers (15% and 10%) will also be regraded prior to testing.

Estimated completion of the physical testing is October 30, 1980. It is envisioned that preliminary data analysis will be completed by January 31, 1981. Assuming no major problems arise, this time frame is realistic based on the progress to date.

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HIGH TEMPERATURE DRYING OF SOUTHERN PINE--A PROCESS ENVIRONMENTAL RELATIONSHIP[1/]

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How high-temperature drying affects mechanical properties of softwood lumber was the topic of a research conference held February 25-26, 1976, at Madison, Wisconsin. Based on his experimental data for southern pine lumber dried at 240°F, Peter Koch found that modulus of elasticity, proportional limit, modulus of rupture, and toughness was not significantly different (0.05 level) from properties of lumber dried at 180°F (1). Since 1976, other experiments (2-4) have yielded similar results. Also, it appears that drying for short periods at even higher temperatures will not significantly reduce major mechanical properties of Number 2 southern pine lumber. For instance, Price and Koch (3) state:

"Number 2 dense southern pine 2 by 6s, 95 inches long were kiln dried in 4-foot wide loads with a 3000-pound top load restraint. The kiln drying regimes consisted of dry-bulb temperatures of 180, 240, and 270°F with wet-bulb temperature of 160°F and kiln times of 120 hours at 180°F; 36 and 120 hours at 240°F; and 9, 36, and 120 hours at 270°F. After kiln drying and a one-year conditioning period, boards were loaded to failure in edgewise bending. From undamaged sections, small clear specimens were removed for evaluation of several properties. Moisture content of loads on emergence from the kiln ranged from 0.2 to 11.9 percent. After one year of conditioning, boards dried at high temperature for a prescribed number of hours had lower equilibrium moisture content than boards dried an equal time at low temperature. Shrinkage was least in wood dried at 270°F for 9 hours. Boards dried at 240°F and 270°F and equilibrated had less average crook, bow, and twist, and less maximum crook and bow than boards dried for 120 hours at 180°F. Boards dried by schedules approximating commercial practice (180°F for 120 hours, 240°F for 36 hours, and 270°F for 9 hours) did not differ significantly in modulus of rupture (MOR), proportional limit, modulus of elasticity (MOE), compression strength parallel to the grain, shear strength parallel to the grain, hardness, and toughness. Regression relationships of MOR to MOE were also similar for the three drying treatments. Boards dried 120 hours at 240°F or 270°F had reduced MOR and toughness; also, regression relationships of MOR to MOE were different from those observed for wood dried on the shorter schedules."

Price and Koch's paper reports property averages for boards and small specimens removed from the boards. Another manuscript in preparation by Dell and Price analyzes distribution of property values. This analysis indicates the distribution of bending strength values, as depicted by a 3-parameter Weibull function, did not differ significantly among the three drying treatments (approximating commercial practice) at any percentile evaluated from the 5th through the 95th. So, strength properties of southern pine Number 2 grade lumber dried with proposed high-temperature schedules (as high as 270°F) do not differ significantly from those of lumber dried with schedules that do not exceed 180°F. Also, prolonged exposure to the high temperatures may alter the strength distribution and other property values. Therefore, additional research related to high temperature drying should establish (1) acceptable and statistically sound procedures to assist when a property change must be incorporated into current design practices (Similar work is currently being undertaken by FPL and ASTM Committee.) and (2) high temperature drying process limitations, i.e., maximum time-temperature exposures for different species and grades of lumber.

1/A summary of the presentation for the Workshop on Research Needs on the Effect of the Environment on Design Properties of Lumber held in Madison, Wisconsin, on May-28-29, 1980.

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VISCOELASTIC BEHAVIOR OF WOOD IN CHANGING ENVIRONMENTS[1]

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INTRODUCTION

Wood is an inherently heterogeneous material. Its behavior is hygroscopically unstable and anisotropically viscoelastic. Thus the full understanding of the responses of its viscoelastic behavior to the service environments is very important to the efficient and reliable design of wood structures. Furthermore, during the kiln drying of lumber and veneer, steaming logs for pelling, and hot pressing of wood composite boards, viscoelastic behavior plays a very important role. Normally, its strong sensitivity to moisture and temperature may induce some undesirable residual stresses. Such stresses are believed to have a significant influence on the development of drying defects in lumber and veneer and the dimensional stability of wood composite boards (3,9,20). However, in other materials, such as toughened glass, the induced residual stresses may be beneficial (13).

In recent years, many findings important to the understanding of time-dependent engineering performance of wood and its composite structures were reported (1,5,6,8,15,16,18, 21,22,24). However, most of their analyses were based on the clear, straightgrain, and defect-free wood subjected to the adjustment of moisture contents, stress level or temperature and each of these adjustments were generally treated independently. Because the interactions of these factors are so complex, wide varieties of information were developed. Based on these experimental findings, mathematical models for the description of the viscoelastic behavior of wood were developed (2,12,14,17). Their predictions of time-dependent deformation behavior of wood are generally satisfactory in one dimensional, simple environmental and loading cases.

More recently, creep models involving the effect of temperature changes were suggested (18). However, information concerning the cases of combined effects of moisture and temperature as well as the heterogeneity of wood, such as knots and holes, are still unavailable. In this report, based on the available experimental findings, the approach to develop a mathematical description with consideration of interaction of these factors is explored.

MICROMECHANICAL APPROACH

Consider a two-dimensional heterogeneous body as shown in Figure 1 which is in the space of a force, a moisture and a temperature field. It is assumed that physically this body consists of many elements of area mass (ΔM) which can be divided into four equal parts of point mass. It is further assumed that each point mass is hingedly-connected with its nearest neighbor by a mechanical bar and each bar represents a four-element creep model. The schematic expressions of this concept are shown in Figures 2, 3 and 4. Such a concept was suggested by Jayne and Suddarth for the analysis of dynamic behavior of heterogeneous materials (10).

In the micromechanical analysis of wood, anatomical features such as earlywood, latewood and wood rays can be considered as different elements of area mass. Similarly, the knotty area can be expressed as a high density area mass while the area of a hole may be treated as the absence of area mass or mechanical bar. Furthermore, the quantity of area mass can be assumed to be dependent on the moisture content and density of wood. Such assumptions can be expressed mathematically as

[1] Paper presented at the Workshop of Research Needs on Effect of the Environment on Design Properties of Lumber, Forest Products Laboratory, Madison, Wisconsin, May 28-30, 1980.

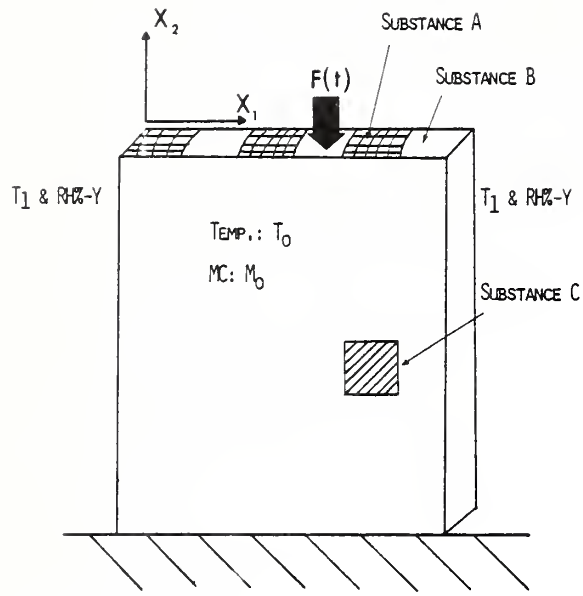

Fig. 1. A two-dimensional heterogeneous body in the space of force, temperature and moisture field

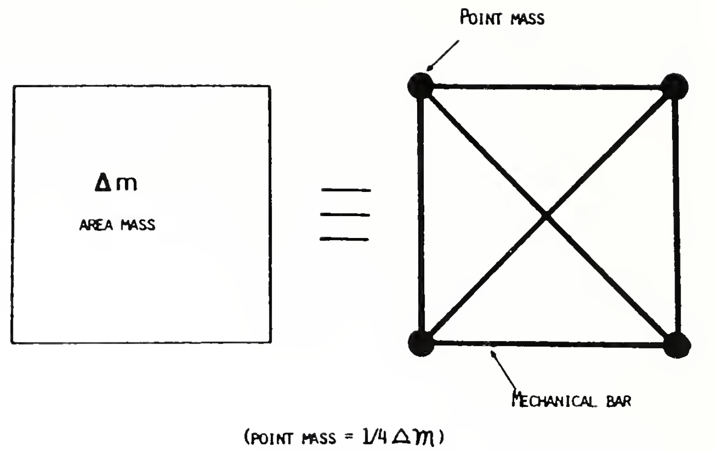

Fig. 3. The elemental area mass and its equivalent space frame

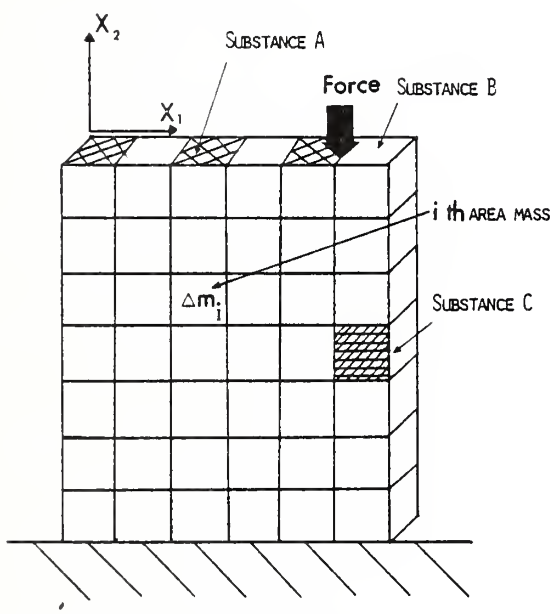

Fig. 2. A two-dimension heterogeneous body consisting many area mass

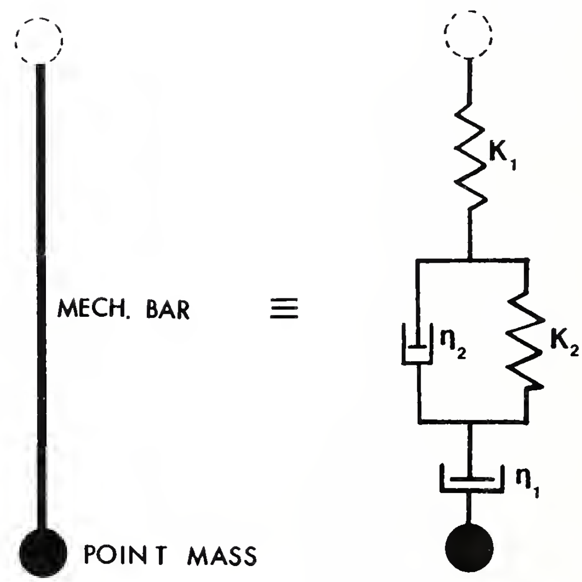

Fig. 4. The equivalent four-element viscoelastic model for a mechanical bar.

$$\Delta m = m\ (M,\ d) \tag{1}$$

where M is the local moisture content and d is the local density.

A generalized mathematical expression for the description of the relationship between force [F(t)] and displacement [u(t)] in a four-element creep model with a point mass attached, as shown in Figure 4, can be written as

$$D^2F(t) + \left(\frac{k_1}{\eta_1}+\frac{k_1+k_2}{\eta_2}\right)DF(t) + \left(\frac{k_1k_2}{\eta_1\eta_2}+\frac{4k_1}{\Delta m}\right)F(t)$$

$$+ \frac{4k_1k_2}{\eta_2\Delta m} D^{-1}F(t) =$$

$$k_1D^2u(t) + \frac{k_1k_2}{\eta_2} Du(t) \tag{2}$$

where $D = \frac{d}{dt}$, and $D^2 = \frac{d^2}{dt^2}$ are differential operators, $D^{-1}=\int_0^t dt$, and k_1, k_2 are elastic constants of the 1st and 2nd spring respectively, and η_1, η_2 are viscous coefficients of the 1st and 2nd damper respectively. Analogous to the Kirchhoff's laws of circuits, the following assumptions are valid for the mechanical behavior of the space frame as shown in Figure 3:

(1) the sum of forces are equal to zero ($\Sigma F(t) = 0$) at each junction,

(2) the sum of displacements, velocities, and accelerations are equal to zero ($\Sigma u(t) = 0$, $\Sigma Du(t) = 0$, and $\Sigma D^2u(t) = 0$) around closed loop.

It follows that a set of 40 ordinary differential equations, which approximates the mechanical behavior of the viscoelastic body as shown in Figure 5, can be generated. With the availability of modern computer technology, these differential equations can be solved for the mechanical responses of arbitrarily shaped viscoelastic bodies under any types of boundary conditions.

It should be noted here that the viscous coefficients η_1 and η_2 of the creep units, as shown in Figure 4, can be expressed as

$$\eta_1 = Ae^{Bz^{\frac{1}{2}}}e^{-\Delta E/RT} \tag{3}$$

$$\eta_2 = A'e^{B'z^{\frac{1}{2}}} \tag{4}$$

where A, A', B and B' are material constants, z is the degree of polymerization, R is the gas constant, T is the temperature in unit of Kelvin, and ΔE is the difference of kinetic energy between two stages of moisture levels. Experimentally, ΔE can be determinated from the vapor pressure of free liquid water at any given temperature.

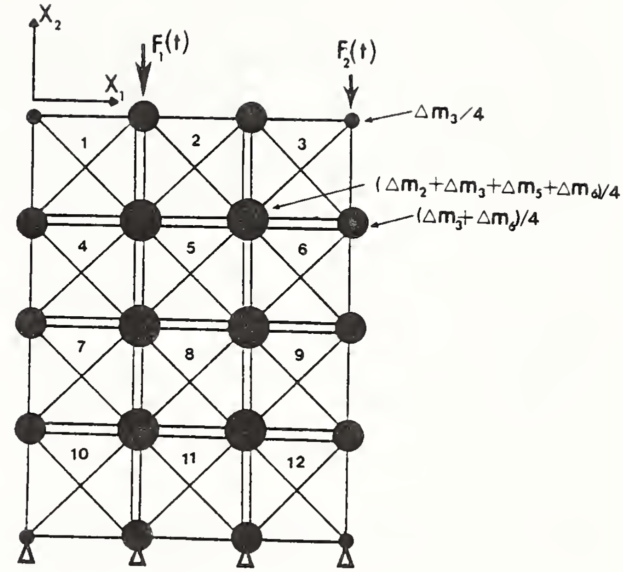

FIG. 5. A SPACE FRAME SUBJECTED TO POINT LOADS

Wood is a cellulosic polymer and it is susceptible to biological, chemical and physical degradations. When the wood is deteriorated, its degree of polymerization will be rapidly decreased. That is, the magnitude of viscous coefficients η_1 and η_2 of the deteriorated zones will be drastically reduced. This suggests to us that one can use equation (2) with equations (3) and (4) to evaluate the time-dependent mechanical behavior of wood structures in a changing environment under the attack of biological, chemical and physical agents locally or wholely.

MACROMECHANICAL APPROACH

According to Halpin (7) and Schapery (19), the constitutive equations for a thermoviscoelastically simple body can be expressed mathematically as

$$\varepsilon_i(\zeta) = \int_0^\zeta S_{ij}(\zeta-\zeta')\frac{d\sigma_j(\zeta)}{d\zeta'}\, d\zeta' \quad \text{[stress history]}$$

$$+ \int_o^{\zeta} \phi_{ij}(\zeta-\zeta', T-T_o)\frac{dT(\zeta)}{d\zeta'}\, d\zeta' \quad \text{[temperature history]}$$

$$+ \alpha_i(T-T_o) \quad (i,j = 1,2,\ldots 6) \qquad (5)$$

where $\varepsilon_i(\zeta)$ are strain responses, $\sigma_j(\zeta)$ are applied stresses, α_i are coefficients of thermal expansion, S_{ij} are anisotropic creep compliances, ϕ_{ij} are thermal induced strains when the body is unstressed and they are given by

$$S_{ij}(\zeta) = S_{ij} + \sum_n S_{ij}^{(n)}(1-e^{-\zeta/\tau_n}) \qquad (6)$$

$$\phi_{ij}(\zeta) = \sum_n \phi_{ij}^{(n)}(1-e^{-\zeta/\tau_n}) \qquad (7)$$

in which $\tau_n = \eta_i^{(n)} S_{ij}^{(n)}$ and η_i's are viscous coefficients. Also

$$\zeta = \int_o^t \frac{dt}{a_T}, \quad \zeta' = \int_o^{\tau} \frac{dt}{a_T} \qquad (8)$$

where a_T is the temperature-dependent shift factor.

The equations (5)-(8) have been applied by Schaffer (18) in the analysis of the temperature-time dependency of longitudinal mechanical behavior of dry Douglas-fir and satisfactory results were reported. However, in general the effects of moisture on the mechanical responses in wood and its composites are much greater than those from temperature. Thus, in most cases the combined effects of moisture and temperature must be considered. In attempting to solve this problem, the following symbolically expressed equation was suggested by Johnson (11) for the description of the mechanical responses of a viscoelastic body when it is subjected to stresses under the combined effects of moisture and temperature.

$$Q[\varepsilon] = P[\sigma] + A[T] + B[M] \qquad (9)$$

where Q, P, A, and B are differential operators acting on the strain ε, stress σ, temperature T and moisture content M field, all of which are time and spatically dependent.

Analogously, equation (9) can be written explicitly as equation (5), that is

$$\varepsilon_i(\zeta) = \int_o^{\zeta} S_{ij}(\zeta-\zeta')\frac{d\sigma_j(\zeta)}{d\zeta'}\, d\zeta' \quad \text{[stress history]}$$

$$+ \int_o^{\zeta} \phi_{ij}(\zeta-\zeta', T-T_o)\frac{dT(\zeta)}{d\zeta'}\, d\zeta' \quad \text{[temperature history]}$$

$$+ \alpha_i(T-T_o)$$

$$+ \int_o^{\zeta} \psi_{ij}(\zeta-\zeta', M-M_o)\frac{dM(\zeta)}{d\zeta'}\, d\,' \quad \text{[moisture history]}$$

$$+ \beta_i(M-M_o) \quad (i,j = 1,2\ldots 6) \qquad (10)$$

in which the β_i's are the coefficients of hygroscopic changes, M and T are the distribution functions of moisture content and temperature respectively given by

$$M = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\sum_{k=1}^{\infty} A_{m,n,k} e^{-\pi^2 t\left(\frac{a_1 m^2}{h_1^2} + \frac{a_2 n^2}{h_2^2} + \frac{a_3 k^2}{h_3^2}\right)} \sin\frac{m\pi x1}{h_1}\sin\frac{n\pi x2}{h_2}\sin\frac{k\pi x3}{h_3} \qquad (11)$$

$$T = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\sum_{k=1}^{\infty} A'_{m,n,k} e^{-\pi^2 t\left(\frac{\rho_1 m^2}{h_1^2} + \frac{\rho_2 m^2}{h_2^2} + \frac{\rho_3 k^2}{h_3^2}\right)} \sin\frac{m\pi x1}{h_1}\sin\frac{n\pi x2}{h_2}\sin\frac{k\pi x_3}{h_3} \qquad (12)$$

where a_i's are moisture diffusion coefficients, ρ_i's are thermal diffusivity coefficients, h_i's are the dimension of wood corresponding to x_i directions, and $A_{m,n,k}$ and $A'_{m,n,k}$ are unknown constants to be determined from boundary conditions in the hygroscopic range. Also, ψ_{ij}'s are the hygroscopically induced strain responses when the body is unstressed and it can be expressed as

$$\psi_{ij}(\zeta) = \sum_n \psi_{ij}^{(n)}(1-e^{-\zeta/\tau_n}) \qquad (13)$$

in which $\zeta' = \int_o^{\tau} \frac{dt}{a_{TM}}$, and a_{TM} is the shift-factor due to hygrothermal effect.

It should be noted here that the moisture gradients given by equation (11) are valid only when the temperature is constant. Similarly, the temperature gradients evaluated from equation (12) are under the condition that moisture in the wood is uniformly distributed. However, to evaluate the time-dependent mechanical behavior of wood in a changing environment, one must consider the mutual influences of temperature and moisture gradients. This suggests that a temperature-, position-, species-, and time-dependent moisture distribution function is needed in the theoretical analysis of wood mechanics.

THE STRESS-TEMPERATURE-MOISTURE

DEPENDENT SHIFT-FACTOR (a_{STM})

Wood is a very complex fibrous polymer. Its mechanical responses are extremely sensitive to moisture change, especially in elevated temperature environments. To describe such responses, the approximate value of the stress-temperature-moisture dependent shift-factor must be determined for the validity of equation (10). Analogous to the temperature-dependent shift-factor equation established by Williams, Landel and Ferry (the so called "WLF equation"), the shift-factor a_{TM} for changing temperature from T_o to T and for changing moisture content from M_o to M, respectively, can be given by

$$a_{STM}^{(i)} = \eta_i S_{ij} / \eta_i^o S_{ij}^o \qquad (14)$$

where η_i^o and η_i are the viscosity of dampers at stress level σ_o, temperature T_o, moisture content M_o and stress level σ, temperature T, moisture content M, respectively, and S_{ij}^o and S_{ij} are their corresponding creep compliances. In reviewing the available experimental data with the application of Doolittle's (4) concept on the free volume-temperature relationship for an amorphous polymer, it is suggested that equation (14) can be physically approximated in terms of the effects of stress level, temperature and moisture distribution, by the Taylor's expansion such that

$$\ell n a_{STM}^{(i)} = \delta_o^{(i)} + \delta_1^{(i)} \left(\frac{\sigma-\sigma_o}{\sigma_o}\right) + \delta_2^{(i)} \left(\frac{\sigma-\sigma_o}{\sigma_o}\right)^2$$
$$- b_i[\alpha_i (T-T_o) - \frac{\alpha_i^2}{f_o} (T-T_o)^2 + \ldots]$$
$$- c_i[\beta_i (M-M_o) - \frac{\beta_i^2}{g_o} (M-M_o)^2 + \ldots] \qquad (15)$$

where δ_i's are emperical constants related to stress level while b_i's and c_i's are empirical constants related to its thermal and hygroscopic characteristics respectively, f_o is the fractional free volume at temperature T_o when moisture content is zero percent, and g_o is the fractional free volume at moisture content M_o when temperature is at T_o.

It should be noted here that at time t_o if the distributions of temperature and moisture are uniform in the wood, then T_o and M_o can be treated as constants. Otherwise, equations (11) and (12) should be used. The equation (15) is similar to the shift-factor equation suggested by Weitsman (23) for the composite material in changing environments except missing the mixed term of temperature and moisture content. His equation is given by

$$\ell n a_{TM} = \lambda_o + \lambda_1 T + \lambda_2 M + \lambda_3 T^2$$
$$+ \lambda_4 TM + \lambda_5 M^2 \qquad (16)$$

in which λ_i's are empirical constants.

To verify the validity of equation (15), a series of experimental works must be conducted to collect sufficient information for evaluating its accuracy and to determine if the mixed term is needed in the analysis of mechanical responses of wood and its composites.

LOADING HISTORIES AND BOUNDARY CONDITIONS

It was proved experimentally that the time-dependent mechanical responses of wood structures are significantly affected by the history of loading conditions, especially in a changing environment. However, most of the available experimental findings are based on the simple mechanical tests such as tension, compression, torsion and bending. The applied forces or deformation are generally distributed uniformly and continuously along the boundaries and in some cases they are symetrically applied to the body, such as centrally loaded or uniformly loaded bending. However, for practical application, the cases involving discontinuous, antisymetrical, or mixed boundary conditions should be also considered.

In general, the mechanical responses of wood and its composite structures can be described, either from micromechanical or macromechanical approaches, under the following six loading conditions:

(1) constant force: $F = F_o$,

(2) constant displacement: $u = u_o$,

(3) constant rate of force: $DF = F_o$,

(4) constant rate of displacement: $Du = u_o$,

(5) sinusoidal force: $F = F_o^{i\omega t}$.

(6) sinusoidal displacement: $u = u_o e^{i\omega t}$

where $i = \sqrt{-1}$ and ω is the angular velocity.

In the cases of multi-step constant loading and multi-cyclic constant loading, the Boltzmann Superposition Principle can be modified and then applied in the determination

of accumulated mechanical responses. However, if the structures are loaded under a changing environment, the effects of residual stresses induced during the previous loadings must be considered in a theoretical analysis.

REMARKS

It seems that the suggested approaches may offer several distinct advantages over some conventional theoretical approaches in the wood mechanics. These advantages are delineated as follows:

(1) The heterogeneous and anisotropic nature of wood and its composites can be introduced readily, and especially in the micromechanical approach. This would seem to be particularly helpful when the adhesive bondings and defects in the structures must be considered.

(2) The prediction of mechanical responses of wood and its composite structures when they are subjected to discontinuous, non-uniform, or mixed boundary conditions under changing environmental or service conditions and degradations can be worked out.

(3) The micromechanical approach is applicable to the prediction of either dynamical or statical responses of wood-based composite structures. Furthermore, it is capable of dealing with nonlinear behavior. In the matter of numerical analysis, a computer program can be established to obtain the solution to the set of ordinary differential equations which approximates the mechanical responses of wood or its composite structures of irregular shape.

To verify the validity of these theoretical approaches, systematical experiments in the determination of all parameters forementioned are needed to be conducted. Particularly, it is suggested that the wood structures associated with growth, seasoning and mechanical (such as notches or holes) defects should be tested. In addition, the size effects on the mechanical responses should be sequentially evaluated to study the influences of stresses or strains to the directional moisture diffusivity.

The hygrothermal stresses developed during the steaming and drying process or chemical treatment of wood as well as in the hot pressing of wood composite boards are known to have significant influences on the time-dependent mechanical and physical behavior. Such information is very limited at present time and it is definitely needed to be investigated. Also, due to the increase of using wood composite structures in the building construction, it seems that the effects of changing environments on the creep-rupture phenomena should be studied. Furthermore, it is suggested that models for predicting the engineering reliability of wood and its composite structures need to be developed.

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SUMMARY OF RESEARCH NEEDS ON LOAD HISTORY FACTORS--

REPORT OF THE TASK GROUP

The group approached the problem by noting what we consider deficiencies incorporated in the present load duration design curve and procedures, and what we could do to correct them. In order of priorities they are:

Problem: The present curve is based on small clear specimens.

Solution: Test commercial sized lumber (e.g., 2 by 4) and a number of different strength groups (e.g., low, medium, high).

Problem: The present curve is based on bending loading mode.

Solution: Test under bending, tension, and short column compression, measuring material parameters that would be necessary for damage or behavior models or design (e.g., viscoelastic parameters, creep, etc.). Other loading modes would be tested after these initial ones.

Problem: Present curve is based on one species, one size, constant moisture content (MC) and temperature (T), with no drying stresses or "treatments" (i.e., chemical or biological).

Solution: Information would be highly desirable to the above problems, but a baseline needs to be established with one species, one size, constant environment condition, and no treatments in three loading modes and one strength group. Single permutations would be made off the baseline to check for: strength group effect, load effect (e.g., impact, dynamic), species effect, size effect, treatment effect, and environmental effect--in each loading mode. A spot check of environment effect on load duration would be made in widely different ambient conditions (e.g., Bakersfield, Calif. and Starkville, Miss.) and controlled variable laboratory conditions (not to exceed reasonable extremes). By proceeding sequentially with spot checks on environmental or treatment conditions that are judged reasonable but worst case, priorities can be changed if significant engineering differences in load duration performance appear.

Supplemental Problem: Limited research on load duration phenomena of mechanical joints. No design criteria are available.

Solution: While this is not concerned directly with Design Stresses of Lumber, the group, along with the 1980 IUFRO S5.02 participants, feels this is an equally important area of research for engineered wood structures.

Problem: Present load duration design procedure assumes the limiting design load is applied for a specific duration (either continuously or cumulatively). Non-limiting design loads are assumed not to affect the load history.

Solution: Investigate various damage and behavior models so that all design loads or load histories (including impact and dynamic loadings) can be taken into account to determine design lifetime.

NOTE: Some idea of necessary input to these damage and behavior models should be anticipated so that they can be measured in the above listed tests.

Supplemental Problem: Loads in design are presently given in terms of mean maximum load for a specific recurrence time interval.

Solution: This subject is related to the workshop, however before a reliability-based load duration criteria for wood using damage and behavior models can be utilized, more than a maximum load is needed. "Typical" load histories will require re-examination and research of climatological data and load survey data. This information may become available from such load groups as the National Bureau of Standards (given wood research guidance).

Problem: Present wood failure, though local initially, is categorized by gross loading conditions (e.g., in bending, failure can start in tension perp to the grain around a knot).

Solution: Investigate localized failure mechanisms (e.g., tension perp and/or shear failure, compression perp and shear failure). Localized failure criteria coupled with a lumber behavior model (with local stresses) would yield load history failures based on a heterogeneous wood structure model.

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EFFECTS OF PRIOR LOADING ON STRENGTH OF LUMBER[1]

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The following comments were prepared for the Workshop on Research Needs on the Effect of the Environment on Design Properties of Lumber, held in Madison, Wisconsin, May 28-30, 1980. Since the volcanic eruption of Mount St. Helens occurred just ten days prior to the opening session of this workshop, a more appropriate title for discussion would be "A Need to Know the Effect of the Mount St. Helens Volcanic Eruption on Structural Properties of Downed Timber," with the following summary:

> The volcanic eruption of Mount St. Helens on May 18, 1980, caused immense damage to the surrounding forested area. Reported estimates of downed timber value over an area of approximately 150 square miles are about $200 million. The timber down in the Gifford Pinchot National Forest alone is estimated at one billion board feet. This is twice the annual cut of the forest and represents about 20% of all of the annual cut in national forests in Washington and Oregon.
>
> Another way to envision the immensity of the damage to the forest is through the potential number of homes that could be built with lumber sawn from the downed timber. This has been estimated at 200,000 homes.
>
> It may be possible to salvage much of this timber but it is not known whether the immense force and heat waves from the eruption have caused internal damage which would limit the utilization of the downed timber. For example, the Columbus Day blow of 1962 caused great damage to the Pacific Northwest forests. The timber salvaged then had a frequent occurrence of compression failures, commonly referred to as timber breaks, which prevented its utilization as structural components. Also in 1962 it was important to get the downed timber out of the forest before it decayed or was attacked by insects. Once that happens, the value of the timber drops rapidly.
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> The allowable design stresses for visually graded lumber are based on actual test data from samples of the various structural species. The allowable design stresses for machine graded lumber are based on correlative results of studies relating stiffness to strength properties of individual pieces of lumber. These established relationships for timber exposed to normal conditions are probably not valid for the timber which has been subjected to the stress and heat waves generated by the volcanic eruption.

The intended comments for this workshop were to be limited to the effects of proofloading on the structural properties of the surviving lumber. The structural properties in flexure, tension and compression are to be considered for three types of lumber. The types of lumber are: (1) Solid Sawn, (2) Fingerjointed, and (3) Parallel Laminated Veneer.

SOLID SAWN LUMBER

Flexure

The greatest amount of research, of course, has been conducted on flexure of solid sawn lumber. On research that has been conducted at Washington State University, it has been found that short term allowable properties in flexure are not adversely affected when a bending proofload does not exceed 2.0 times the allowable design stress for a given

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grade of lumber. Admittedly, a proofload of 2.0 times the allowable design stress for some of the surviving pieces of lumber is very near ultimate failure. The type of failure at these low stresses, however, are almost always tensile failures. Compression failures do not normally occur at relatively low stress levels.

Tension

Research efforts have verified that there is very little, if any, degradation of ultimate strength when prestressing in tension. Therefore, tensile stressing should be the preferred mode of proofloading for members to be used both in flexure and tension. The question now arises as to the relationship of tensile properties to bending properties. The answer to this question is the objective of a research study currently underway in a combined effort of the U.S. Forest Products Laboratory, the University of Wisconsin, Purdue University and Washington State University.

In this study the strength properties are known to be related to other properties that can be determined nondestructively, such as density, grain slope, knot area, moisture content, temperature, elastic modulus, and rate of stress wave propagation. There is good evidence that the strength properties are related to one another. Proof testing methods are used to examine the properties of pieces of lumber which are known to exceed selected proof stress levels of another property.

For example, to investigate the relationship between tension and bending strength, the effect of removing the low tension strength material in a sample upon the bending strength of the remaining material in the sample will be indicative of the correlation between the tension and bending strength.

The results of this combined study will be available in the near future.

Compression

Research efforts in flexure have shown that the reduction of flexure strengths in cyclic loading can be traced to the compression zones in the members. Additional research efforts on compression in full-sized members is done in the above described combined study, and as mentioned above, the results will be available in the near future.

FINGERJOINTED LUMBER

Flexure

In a research project for the American Institute of Timber Construction, it has been found that proofloading in flexure is useful in checking the structural integrity of fingerjoints, providing the proofload level be limited to a maximum level of stress. Flexural proofloading for fingerjoint integrity is currently being practiced by Weyerhaeuser. Also, equipment for applying a flexural proofload in one direction is commercially available through Mann-Russell Electronics, Tacoma, Washington.

Tension

Tension proofloading is the recommended mode for checking the structural integrity of fingerjoints for the same reasons described above for solid sawn lumber. The recommended stress level for tension proofloading is 1.8 times the intended allowable design load in tension. This recommended value has been reduced to near 1.0 by some of the lumber associations because they claim that there is no need to proofload the lumber but only the glue line itself. This, of course, assumes that the strength properties of the glue lines are independent of load duration and the other variables that make up the standard 2.1 factor.

Tension proofloading for fingerjoint integrity is currently being practiced by several companies. Equipment for tension proofloading is commercially available from Metriguard, Inc., Pullman, Washington.

Compression

The author is not aware of any studies on fingerjointed lumber which would indicate that the compressive properties are any different that those for solid sawn lumber.

PARALLEL LAMINATED VENEER LUMBER

There is little data available for similar relationships on parallel laminated veneer lumber. This is due to the fact that parallel laminated veneer lumber is a relatively new product.

Research efforts on the effects of prior loading on strength of lumber are needed in all of the above areas described.

EFFECT OF TEMPERATURE AND MOISTURE CONTENT ON DURATION OF LOAD CHARACTERISTICS OF LUMBER[1]

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ABSTRACT

There is a lack of current information on the effect of temperature and moisture on lumber duration of load characteristics. A potential effect does exist, however, as creep and creep-rupture performance of small clear wood specimens is greatly affected by large variations in the environment. Suggestions are made for future research with particular emphasis toward establishing a cumulative damage or load history model that incorporates effects of temperature and moisture content interactions with load history.

INTRODUCTION

We know very little about the effect of temperature (T) and moisture content (MC) on the duration of load capabilities of lumber. This paper is a short summary of research reports on the subject, or that relate to the subject. Included in this are results on creep and creep-rupture, mainly on small clear wood specimens, and predominantly for cyclic environmental conditions. Creep-rupture will be considered first. Suggestions for future research are given at the end of this paper.

CREEP-RUPTURE

Lumber

It seems that only one study (Kingston and Armstrong 1951) pertains to creep-rupture in lumber sized specimens. In that study Kingston and Armstrong evaluated creep and creep-rupture results on mountain ash beams of 2 by 4 or 3-1/4 by 3-1/4 inches in cross section that were placed under constant load while green and allowed to dry out while loaded. Drying time took about 1 year but some tests were continued out to 900 days. Several beams failed early in the test; but, for those surviving out to a year, deflection at 1 year was about four times the initial deflection. One-quarter of the beams loaded at 4,000 lb/in.^{2} were reported to have failed in less than 10 months, some in 1 or 2 weeks. While the authors did not state a relative stress level (SL), that is the constant applied stress as a percent of static strength, the applied stress of 4,000 lb/in.^{2} is estimated to be about 50 percent of the 25 percent static strength lower exclusion value (based on an assumed green modulus of rupture (MOR) of 9,000 lb/in.^{2} for the species, coefficient of variation (CV) of 16 percent and normal distribution). Several beams loaded at 6,000 lb/in.^{2} failed within 10 days, while one beam loaded at 2,000 lb/in.^{2} failed in about 7 months. By comparison, Wood's (1951) results for small clear Douglas-fir specimens at constant MC show much longer durations of constant stress for comparable relative SL's. The implication is that creep-rupture life is shortened if wood is allowed to dry out while carrying a significant load.

Small Clear Specimens

For a further understanding of the potential effect of a changing environment on duration of load characteristics of lumber, it is necessary to look to the effects reported for small clear wood specimens. Humidity cycling has been shown to cause early failure in very small wood beams under constant loading (Anon

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1962, 1963; and Hearmon and Paton 1964). Beech 2- by 2-mm (0.08- by 0.08-in.) beams loaded to 1/4 or 3/8 of maximum load (moisture condition associated with maximum load was not stated) were reported by Hearmon and Paton to have failed within a few months or less when relative humidity (RH) was cycled as a square wave between 0 and 93 or 100 percent on a 48-hour cycle. Under a constant environment, such load levels would not be expected to cause failures in less than several decades. Failure of the Hearmon and Paton beams occurred after considerable creep deflection. Their report shows that creep increased during each drying phase of the humidity cycle but only during the wetting phase of the first cycle. Loading started under the dry phase. Some creep recovery appeared to occur during subsequent adsorption phases.

Others have reported on the effect of humidity cycling. Bethe (1969) evaluated bending creep of pine sapwood 7- by 7-mm (.28- by .28-in.) beams during six square wave humidity cycles between 90 and 30 percent RH. Several variables pertaining to wood quality and stress level were included in the experiment. Nine of his specimens, a small portion of the total, failed during cycling RH under a relatively low level of stress; but those nine tended to be on the low distribution end of specific gravity or modulus of elasticity.

Schniewind (1967) with a followup study by Schniewind and Lyon (1973) evaluated the effects of both humidity and temperature cycling on creep-rupture life of Douglas-fir beams 1 cm deep (.39 in.) by 2 cm wide (.79 in.) under constant loading. Those two studies provide the best quantification of the cycling effect on creep-rupture life to date. One portion of the studies evaluated constant SL as a variable under both a constant environment and a square wave RH cycle. The main portion, however, evaluated the effect of a variable environment on creep-rupture life at a bending SL estimated at 70 percent of static bending strength. All specimens were started under load at a nominal 12 percent MC and the first phase of a cycle was set to cause drying and/or rising temperature. Results from the constant SL as a variable show that the cyclic RH condition (24-hour period square wave with 35 pct minimum and 87 pct maximum, 75° F constant temperature) greatly reduced the creep-rupture life from that for a constant environment. Their experimental conditions and results for the 70 percent SL are summarized in table 1. Some important conclusions of the study include:

1. Creep-rupture life is shortened by cyclic environmental conditions, both T and RH being contributing factors.

2. A square wave RH cycle causes a greater reduction in creep-rupture life than a sine wave RH cycle, probably because the square wave causes a larger and faster MC change than the sine wave.

3. The minimum cross sectional dimension may be a very important variable interacting with cyclic RH, the smaller the specimen the greater the reduction in creep-rupture life.

4. A larger RH cycle seems to lead to a shorter life.

5. Creep-rupture life seems to be related to amount of change in MC during RH cycling.

Besides the conditions causing a change in MC, a limited amount of research has dealt with constant T or constant MC as variables. Bach and Pentoney (1968) reported on creep tests of hard maple made at various SL's in tension parallel to the grain under various levels of constant T and constant MC. The specimens had the cross section reduced to 3.5 by 4.5 mm (.14 by .18 in.). They reported that 10 of 18 specimens loaded at 78 percent of estimated static strength for a specified T and MC level failed prior to the 1,000-minute duration planned for creep measurements. Failures were about equally scattered among the various T and MC levels evaluated. The failures demonstrate that creep-rupture can occur in tension as well as in bending.

Okuyama (1974) evaluated the effect of constant T on bending strength or bending creep-rupture life of 1- by 1-cm (.79- by .79-in.) Hinoki beams at zero MC. Part of his experiment dealt with effect of strain rate on bending strength and part with effect of constant load level on creep-rupture life. His results were summarized by two equations:

$$\text{(Strain-rate) } F_r = 1950 - 0.129T\,(21.9 + \log t)$$

$$\text{(Constant load) } F_c = 2100 - 0.157T\,(21.9 + \log t)$$

where F_r is bending strength and F_c bending stress in kg/cm^2, T is absolute temperature (°K) and t is the time in minutes. The first equation can be used to estimate static strength at room temperature (MOR = 1081 for a 5-minute test). Division of the equations

Table 1.--Creep-rupture life at 70 percent stress level under various environmental conditions according to Schniewind and Lyon (1967 and 1973)

Cycle	Temperature	Relative humidity	Change in moisture content	Mean time to failure[1]
	°F	Pct	Pct	Min
None[2]			0	103,000
Square wave	75	35 to 87	6.6	1,445
Square wave[3]	75	35 to 87	4.3	2,160
Square wave	75	48 to 78	2.5	6,825
Sine wave[4]	60 to 90	35 to 87	2.0	7,950
Sine wave[5]	60 to 90	65 to 68	0.2	9,111
Square wave[6]	75	35 to 87		24,400

[1] Based on the estimated mean of log times to failure.
[2] Standard humidity room maintained for 12 percent wood moisture content.
[3] Twelve-hour period, all other cycles on a 24-hour period.
[4] Temperature and relative humidity 180° out of phase.
[5] Relative humidity varied to maintain constant moisture content.
[6] Specimen size 2 x 2 inches spanning 40 inches, all others 1 x 2 centimeters spanning 22 centimeters.

by the static strength estimate and multiplying by 100 percent results in the following equations for T = 25° C:

$$(\text{Strain-rate})\ SL_r = 102.5 - 3.6 \log t$$

$$(\text{Constant load})\ SL_c = 99.5 - 4.3 \log t.$$

When compared to Wood's (1951) Douglas-fir constant load data for 6 and 12 percent MC, Okuyama's results suggest a log time coefficient for wood at zero MC on the order of 50 to 60 percent of that for wood in the air-dry condition.

A study by Rose (1965) on oscillating fatigue loading of pine heartwood in tension or compression parallel to the grain at various levels of constant T and constant MC does not exactly fit the subject matter, but it does contain related and useful results. Specimen cross sections were 19 by 20 mm (.75 by .79 in.) in compression and 4 by 20 mm (.16 by .79 in.) in tension. Loading was oscillated from near zero to a specified maximum at about 40 Hertz and was terminated by specimen failure or 3.5 (10^6) cycles (24.3 hr.), whichever came first. Compression was found to withstand a higher relative SL than tension. A SL of 75 percent generally did not cause failure before 3.5 (10^6) cycles of compression, but some failures occurred a 60 percent SL in tension and 65 percent SL generally caused failure in tension. It should be noted, however, that actual peak cyclic stress was about twice as high in tension as in compression due to the differences in static strength (small clear specimens).

The relatively short time to failure in tension in Rose's experiment may be due to a change in T and MC as the oscillating conditions reportedly caused specimen temperature to increase and MC to decrease. Rose measured specimen surface temperatures as high as 15° C over ambient at the higher oscillating stress levels, and interior temperatures were claimed to be 1 or 2° C higher than surface T. Specimen MC decreased by up to 2-1/2 percent, depending on stress level and ambient conditions.

CREEP

As creep in wood is known to precede failure in many cases, an understanding of the effect of a variable environment on creep may be useful in predicting creep-rupture. As with creep-rupture, almost all creep research on wood has been done with small clear wood specimens rather than lumber. The reader may wish to refer to Schniewind's (1968) review on rheology of wood and Nielsen's (1972) document on rheology which go into more depth on creep than given here.

Lumber

Kingston and Armstrong's (1951) research on lumber has already been summarized under the section on creep-rupture. There does not seem to be any other research reported on creep in lumber. Two studies pertaining to creep in glulam beams are of interest. Ranta-Maunus (1975) reported that, at 1 year under constant loading outdoors, pine glulam beams 95 mm (3.74 in.) wide by 176 mm (6.93 in.) deep without protective cover had 2-1/2 times the creep of similar beams protected by a plastic cover.

Bohannan (1974) evaluated Douglas-fir glulam beams 3-1/4-inch wide by 5-1/16-inch deep in bending creep under constant load for 8 years. Constant loads were about 16 to 26 percent of ultimate loads. During the first 3-1/2 years, the beams were indoors where temperature ranged between about 60 and 90° F and RH ranged between about 20 and 50 percent. During the remaining 4-1/2 years, the beams were in a Madison, Wisconsin outdoor climate but with a roof coverage to protect from precipitation. Throughout a typical year, Madison temperature ranges from below 0° F to above 90° F and RH ranges from about 35 percent to 100 percent. Bohannan's creep data do not show any consistently different trend during the outdoor exposure from that during the indoor exposure, but there were fluctuations in the data that Bohannan observed may have been T-MC dependent. Overall, creep deflection after 8 years was about 1/2 the initial elastic deflection.

Small Clears

Reference has already been made to the rapid creep-rupture of very small wood beams under cyclic RH conditions (Anon 1962, 1963; Hearmon and Paton 1964). In that work Hearmon and Paton started their load tests with wood in the dry state; so initially there was 24 hours of creep in the dry state. During the next 24 hours when humidity was maintained at a very high level, additional creep occurred. Then during each subsequent humidity cycle, creep was observed on desorption and creep recovery on adsorption. Much larger creep deflections were observed under cyclic RH than under a constant high RH.

Several other reports; Armstrong and Kingston (1962), Bethe (1969), and Erikssen and Noren (1965); show qualitative agreement with Hearmon and Paton's creep results for cyclic RH conditions, namely that creep increases during desorption and seems to recover during adsorption. Armstrong and Kingston (1962) used several species in evaluating tension and compression parallel to the grain as well as bending; however, their results for tension showed an opposite trend, namely that tensile creep tended to occur during adsorption. Cross sections of specimens were 3/8 inch square for tension, 1-1/2 inches square for compression and 3/4 inch square for bending. On the other hand, Erikssen and Noren's (1965) results for tension parallel to the grain of pine with 0.4- by 5-mm (.02- by .20-in.) cross section qualitatively agree with Hearmon and Paton's results.

Although results are not as dramatic as for cyclic RH, results for creep under monotonic increases or decreases in MC are interesting. Armstrong (1972) showed that creep in compression parallel to the grain for 1-inch square bunya pine was at least twice as large under a desorbing condition than for an adsorbing condition. Christensen (1962) observed that bending deflection of klinki pine 1/2 mm (.02 in.) deep by 1-1/2 mm (.06 in.) wide increased with increasing size of change in MC, either for adsorption or for desorption. Also, Christensen observed that bending creep was much less if a given change in MC was made in two steps rather than in one step. Although not creep but relevant, Urakami and Fukuyama's (1969) results for 1- by 10-mm (.04- by .79-in.) Hinoki indicate that torsion stress relaxation was much greater during adsorption than under a constant MC condition.

Information concerning creep behavior under a changing T are about as limited as for a changing MC. Kitahara and Yukawa (1964) observed bending creep of wet 10-mm square (.79-in. square) Hinoki at three different constant T's (20, 30, or 40° C), then increased temperature to 50° C in 4 minutes or 40 minutes. Their results indicated that creep was greater the higher the temperature or the higher the increase in temperature, but the rate of change in temperature did not seem to affect total creep after a short period of time. Sawabe (1971) observed bending creep of 2 mm (.08 in.) deep by 7 mm (.28 in.) wide Hinoki and Makanba near zero MC at constant T, and then as T was increased 4° C per minute. Sawabe's results show an increased rate of creep as T rose and passed 93° C, his estimate of thermal softening point for wood. Hillis and Rozsa (1978) also reported thermal softening points based on creep of 5-mm square (.20-in. square) Radiata pine in torsion as T increased from 30 to 130° C at 6° C per minute. Changes in creep rate were observed by Hillis and Rozsa at 78, 85, 92, and 104° C in green wood but none was found for dry wood.

Without further comment, the reader may wish to refer to literature on creep under various levels of constant T or constant MC; Armstrong and Kingston (1962), Bach and Pentoney (1968), Kitahara and Okabe (1959), Kitahara and Yukawa (1964), and Norimoto, Miyano, and Yamada (1965).

DISCUSSION

The pronounced effect of wide changes in MC on creep and creep-rupture of small clear specimens suggests the need to consider whether such effects are of concern in lumber. Schniewind and Lyon's (1973) results for 2- by 2-inch-size bending specimens indicate a shorter creep-rupture duration under cyclic RH than under constant RH, suggesting the need for concern about 1-1/2-inch-thick dimension lumber.

Results of Foschi and Barrett (1980) given at a recent IUFRO meeting are possibly relevant. They present cumulative distribution curves for log time to failure of 2 by 6 dimension lumber under constant bending load. Their specimens were tested in a building where heat was provided in the winter but there was no humidity control. Their cumulative distribution curves show an increase in log time failure rate during the latter part of a 1-year loading period. While the authors treated the increase as an effect associated with a particular load-damage model, such an increase might be attributed to a cumulative effect of a variable specimen moisture content.

Most wood structures are not very heavily loaded and perhaps that mitigates the effects of a naturally occurring, variable environment. Parts of some wood structures, however, may carry relatively high loads during a general change in MC such as can occur in a northern climate early in the heating season. Components of particular interest would be:

1. The tension chord of a roof truss carrying a snow load, where the tension chord is covered by thick insulation, and

2. A floor joist or truss floor joist carrying a heavy appliance or perhaps a piano.

Both types of components could undergo a significant change in MC while under heavy load.

While present concepts (Foschi and Barrett 1980) suggest a cumulative loss in duration of load characteristics for wood while under load, at least above a certain threshold, it is interesting to speculate whether wood can recover any of that loss during periods when there is no load or loading is minor. For example, the tension chord mentioned above would only carry a small load when the heating season ends. The question can be posed whether any of the duration of loading loss is recovered, for example, during the spring when MC increases in the tension chord while loads are small.

SUGGESTIONS FOR FUTURE RESEARCH

The need for research on T and MC effects on floor joists and tension truss chords has already been mentioned in the preceding discussion. Our ignorance is not limited to those specific examples, however, as we know essentially nothing about the quantitative effects on any lumber mechanical property. Present design recommendations (NDS) offer very little guidance beyond cautionary statements about temperature and moisture effects, and those deal with allowable properties rather than duration of load. This suggests a complete lack of research data on all types of mechanical properties as to how duration of load capability of lumber is affected by: (1) temperature level, (2) moisture level, and (3) changes in temperature and moisture level resulting from a variable use environment. These research needs are complicated by the lack of quantitative data on duration of load characteristics of lumber under constant environmental conditions, but research is underway or in the planning stage to fill that void.

Some cumulative damage models have recently been proposed which can be used to relate failure time to load history. Current duration of load research is designed to verify the models and quantify model parameters. The effects of T and MC have not been considered in the development of these models, however. Constant T and MC and variable T may be relatively easy to include in a cumulative damage model. Accounting for the effects of a variable MC, however, is complicated by the fact that creep increases during loss of moisture, but so does static strength.

Therefore, the effect of systematic variations in T and MC on duration of load should be quantified to help establish a more complete cumulative damage model. At least one mechanical property of lumber should be evaluated, say bending or tension. The systematic variations in T and MC could be patterned after Schniewind (1967), but one phase should be set up to evaluate differences in duration of load between specimens loaded only during desorption and specimens loaded

only during adsorption, with both types under identical cyclic humidity conditions. Primary emphasis should be on MC rather than T as loads are expected to be low when any structural light frame components, roof truss compression chords for example, are at a significant high temperature. Wood cooling towers are an important exception, however, because high structural loads generally coexist with high temperature and moist conditions.

Especially for bending, including combinations with compression such as in truss top chords or studs in wood foundations, a duration of load model should be developed for deflection due to creep and/or partial failure. Experience in ramp uploading bending tests (constant rate of uploading) of lumber with edge knots shows that specimens generally crack at loads well below the ultimate failure load. Each crack results in a sudden increase in deflection. The important consideration is that deflection becomes large long before maximum load is reached. Such deflections are visible and would likely be considered excessive in structures, although strength may be adequate. Corrective action such as shoring or component replacement would make the structure "visually safe." One example is the excessive sag that was noted in the 1960's in old apartment house floors that were to be rehabilitated. The apartment floors seemed to be sound except for the sag, which had to be corrected before repartitioning the buildings.

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STRATEGIES FOR RESEARCH ON THE EFFECT OF THE ENVIRONMENT ON THE PROPERTIES OF LUMBER[1]

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ABSTRACT

A brief discussion of some factors that should be considered when planning research on the effect of the environment on the properties of lumber.

The use of wood as load-bearing elements in structures necessitates the ability to make two kinds of predictions: one centers around the anticipated loads and conditions of use, including environmental factors such as moisture, temperature, weather, biological agents, and the other centers around the ability of wood or lumber to carry these anticipated loads under the anticipated conditions of use and environmental factors. Predictions of the first kind are often codified, and at first glance appear to be outside the scope of this workshop. However, closer examination suggests that the deliberations of this workshop ought to start with predictions of the first kind. While some of the factors involved, such as loading, are independent of the type of structural material used, others will be of significance only to particular materials. We can, therefore, expect that for lumber we need to be concerned with a special set of factors, and this must be identified.

Furthermore, before venturing to make predictions of the second kind, we need to know what range of each factor should be of concern to us. For example, structural lumber is known to be used at a wide range of moisture content levels, anywhere from green to very low levels of moisture content. The question is one of deciding how low a moisture content should be of concern. We know that in small, clear wood specimens the strength-moisture content relationships change when the moisture content becomes less than about 8 percent. We do not really know if the same applies to lumber, or even if it is important. Another example might be temperature. What are the minimum and maximum temperatures that we ought to be concerned with?

While moisture content and temperature are important factors in themselves, i.e., while they have a direct effect on lumber properties, they are likely to interact, not only with each other but also with other factors such as biological agents. The dependence of rate of decay on temperature and moisture content is a well known example.

Once we have decided what factors we must anticipate, and at what levels, we can proceed to predictions of the second kind. Here it might be useful to take time for a survey of the scope of the problem. First of all, lumber is made from a variety of species, it is made to fall into one of five grade classes (Light Framing & Stud, Structural Joist & Plank, etc.), all but two of which differ on the basis of size, and within each grade class there are from two to four grades that presently have assigned to them permissible design properties (standard, select structural, No. 1, etc.). If we take the major softwood species or commercial species groups, and add a few hardwoods, it can be argued that we should be concerned with about 20 species. In addition we should probably look at each of the grade classes, with, say, two grades in each grade class.

[1] Remarks prepared for the Workshop on Research Needs on the Effect of the Environment on Design Properties of Lumber, Madison, Wisconsin, May 28-30, 1980.

This amounts to a total number of combinations of type of lumber of 200 (20 species x 5 grade classes x 2 grades).

Next, there are a number of properties that will be of importance. Present practice is to assign six allowable properties to each grade (F_b, F_t, F_v, $F_{c\perp}$, F_c, and E). While one of these is not grade dependent, there are a number of other properties not included in the list of six, namely those that relate to design values for mechanical fastenings in wood, e.g. nails loaded in withdrawal or laterally, bolts, screws, and ring connectors. Altogether this amounts to about the equivalent of six properties varying over all the grades. If we consider these for all combinations of material, we come to 1200 values (200 types of lumber x 6 properties).

Let us now assume that there are only five environmental factors that ought to be considered, each with its own complexities. That would then mean, assuming that we started from the very beginning, that we are faced with the need for 6000 investigations, each comprising many experiments considering that each factor must be explored at various levels, that there may be various interactions, and that there must be replications.

Without being too concerned with the details of the foregoing calculations, they nevertheless show that potentially the scope of the research is enormous. There is, of course, much that is already known, but even with the better known factors our knowledge is often surprisingly limited. Take, for instance, the effect of moisture content on tensile strength parallel to grain. Current practice places it on a par with the effect of moisture content on bending strength, but the few data available suggest that at least in some species there is little or no increase in tensile strength due to drying for small, clear specimens. This leads to a number of observations. We have learned from hard experience that defect-free wood and lumber are not the same. We know that not all properties are affected to the same extent by any given factor. Not all species react the same. Thus it is clear that while it would be absurd to contemplate carrying out 6000 investigations, we must be careful in how we approach the required streamlining and how we design our experiments.

Confronted with such a vast array of potential research tasks, we can approach it by identifying the areas of greatest need, and then proceeding to make experiments. Such experiments could be designed to get data that have potential usefulness, using the best judgment available on the basis of present knowledge. This could proceed in the hope that eventually enough data will have been collected so that a cohesive picture emerges, with the ultimate aim of producing a model that can be used for quantitative predictions of the factor or factors of concern.

Such an approach will no doubt produce results, and will produce some of them very quickly. There is the danger, however, that once the model has been found, a good part of the previously obtained data will turn out to be defective because they cannot be interpreted in terms of that model. A good example is the area of the rheological behavior of wood. Many investigators in many parts of the world have extensively worked and published in that area. Yet, much of the work was done without a clear understanding of the theory of viscoelasticity. At least partially as a result of this, and because of an emphasis on influences rather than on numbers, we have now very little in the way of quantitative information on creep or stress relaxation of wood that might be used in design.

Because of the dangers inherent in not doing so, the development of models should be made not only the principal focus of attention but also given first priority. It is probably safe to say that among the environmental factors that will be considered at this workshop, none will be a complete unknown. Thus there should be existing information, which may, of course, vary in extent depending on the specific subject area, that can be analyzed and used for model information. Only after a theoretically sound framework of reference has been established can we expect to be able to collect data that will be meaningful and of lasting value.

The fundamental strategy that should therefore be used in attacking the problem of how to deal quantitatively with the effect of the environment on the properties of lumber is to place model development ahead of extensive experimentation in our list of priorities. Such an approach, although more difficult initially, will ultimately bear great dividends in terms of research efficiency and general usefulness of any data obtained.

A PERSONAL VIEW OF TIMBER ENGINEERING RESEARCH PRIORITIES

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ABSTRACT

Research priorities in the Timber Engineering field are discussed as they relate to the present design specifications. It is stressed that engineering solutions are being sought. The priorities are developed using the criteria; magnitude of indicated change, safety considerations and how widely the indicated changes will be employed in design of timber structures.

INTRODUCTION

Timber Engineering is a field where tradition, plus some research, has led to a design system which by and large has given acceptable structures at least from a safety point of view. However, a lot of inconsistencies do exist within the system. Much of the knowledge derived from research on wood properties of small clear specimens is unfortunately irrelevant in the way it has been applied in our design codes. It is more the sound engineering judgement of the code committee members than research that has prevented us from making serious mistakes. We can only hope that the research in the future will be more relevant to Timber Engineering and that innovative approaches will prevail.

Some of the shortcomings in our knowledge of Timber Engineering will be discussed in the following, together with needs for research. The remarks can be divided into four classifications. Some are based upon facts while others are based upon preliminary information. Others may be classified as hunches and, finally, some may be considered as wishful thinking. The remarks deal primarily with the strength of single members and must be appropriately modified for multiple member systems.

The effects of moisture content will be discussed first. Next, a short presentation will be given regarding some "Duration of Load" experiments. This will be followed by recent experience with In-Grade testing. This, in turn, will lead to a suggested list of priorities for research needed in the Timber Engineering field.

MOISTURE CONTENT EFFECTS IN BENDING

It has long been known how moisture content affects the strength and stiffness of wood. This information has been transposed to our design codes dealing with lumber. The design stresses in bending for wet material are thus 16% less than those for dry service conditions. But is it correct that our experience with wood (small clear specimens) can be transferred to lumber? A fairly large bending experiment has recently been completed which addresses that question [1].

The purpose of that investigation was to find out what happens to the strength and stiffness of lumber as it dries out on the job site. Two typical situations were considered:

A) The lumber arrives wet on the job site. It is used for framing immediately and is allowed to dry out slowly.

B) The lumber arrives wet on the site but due to some delay it is left exposed to the elements for some time before it is finally covered and left to dry.

Condition A was simulated by letting wet lumber dry out in the laboratory. Condition B was simulated by first exposing the lumber to the weather for three months (February-May) before it was brought into the laboratory and left to dry out by itself.

These tests were compared to tests with wet lumber which were left to equilibrate in a room with set relative humidity conditions. Thus, three dry-out methods could be compared. A difference in the results due to the dry out method could not be detected in the moisture content range from 10% to 25%.

The matched sample technique was used in these tests employing 150 replications for each test condition. Ten test conditions were used for each of the three species groups: Douglas fir, Hem-Fir and Spruce-Pine-Fir. The total program resulted in 4,500 pieces, 2x6" boards of "#2 & better" grade being tested to destruction. The strength versus moisture content results are shown in Figure 1 for Hem-Fir. The strength at the different percentiles were calculated from three parameter Weibull distributions fitted to the data sets.

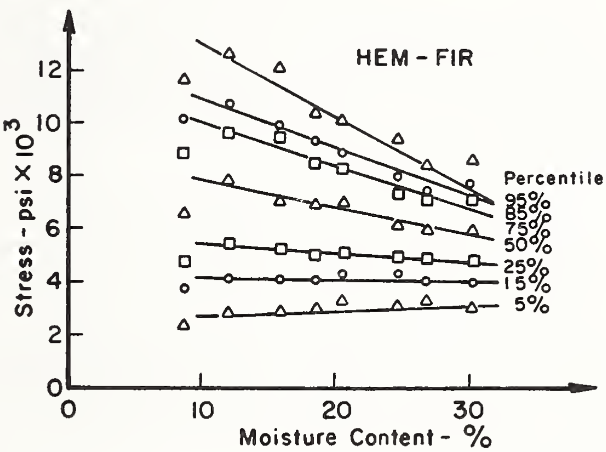


Figure 1.--Stress versus moisture content Hem-Fir.

The first observation which should be made is that the spread in the data increases as the moisture content decreases. Secondly, it can be seen that the material in the upper portion of the strength distribution increases in strength as the moisture content decreases, just as for wood. However, the material in the lower portion of the strength distribution gets slightly weaker as it dries out. This shows that wet material is somewhat stronger than dry material at the 5th percentile level.

This is in sharp contrast to our present understanding of the moisture effect on lumber as expressed in our design code. However, if one considers the failure modes involved, the new results make a lot of sense. The material in the upper portion of the strength distribution has a ductile failure mode associated with compression just as small clear specimens have. On the other hand, the material in the weaker portion of the strength distribution fails in a brittle fashion in the tension zone often associated with local grain disturbances. As the material dries out, it becomes more and more brittle and hence weaker. The effect moisture content has on strength is thus a function of strength. This is shown in Figure 2 where the percent change in strength per percentage point change in moisture content is shown versus strength. It was observed that there were slight differences in behaviour between the three species groups tested. Modulus of elasticity was found to be affected by moisture content. However, stiffness in terms of ExI was, as shown in Figure 3, hardly affected by changes in moisture content.

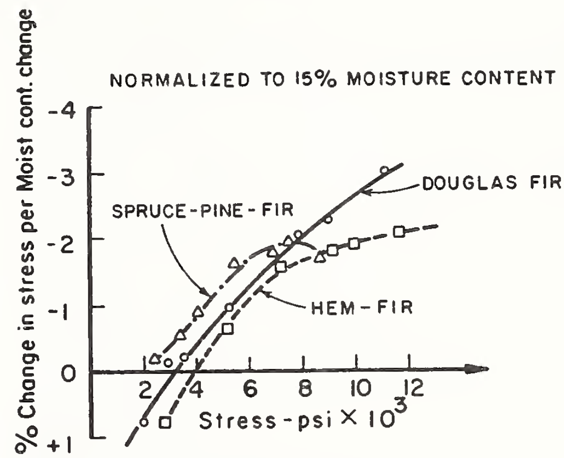


Figure 2.--Percent change per percentage point change of moisture content versus stress.

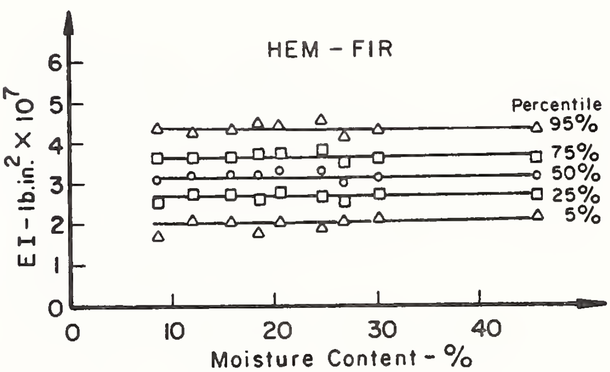


Figure 3.--Stiffness (ExI) versus moisture content. Hem-Fir.

Further work is presently going on exploring the moisture content effects for tension, compression and shear.

DURATION OF LOAD

The first duration of load experiments conducted at U.B.C. in 1971 [2] [3] using 2x6 lumber were interpreted as showing that the duration of load effect was a function of the strength of the material. A stepwise ramp-loading was used in these experiments which makes the interpretation somewhat difficult

and the validity of the results were questioned. Admittedly, the statistical basis was weak compared to the today's practice because only 30 replications were used for each test condition. Subsequent investigations [4], in which 4,000 pieces of 2x6s were subjected to constant stress, also revealed a tendency for different behaviours at different strength levels. Figure 4 shows the results in the traditional fashion as stress level versus log time (hours). However, in this case a separate curve has been drawn for each stress level rather than a single curve for all the data points. The number of specimens on which the curves are based are shown on top.

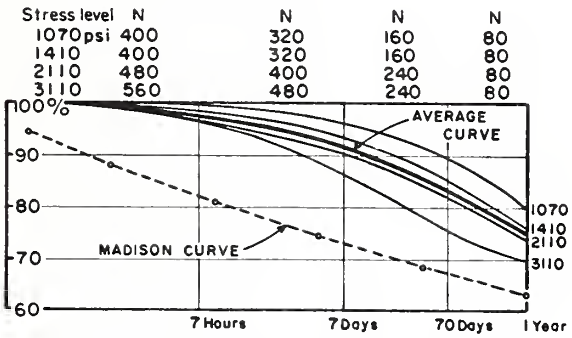


Figure 4.--Stress ratio versus log time. Constant load test.

The results from a third experiment, carried out by Dr. Spencer [5], dealing with the effect of rate of loading are shown in Figure 5. The logarithms of time to failure are shown along the x-axis while the strengths are shown along the y-axis. Again, one is tempted to conclude that the time related behaviour of lumber is dependent upon strength.

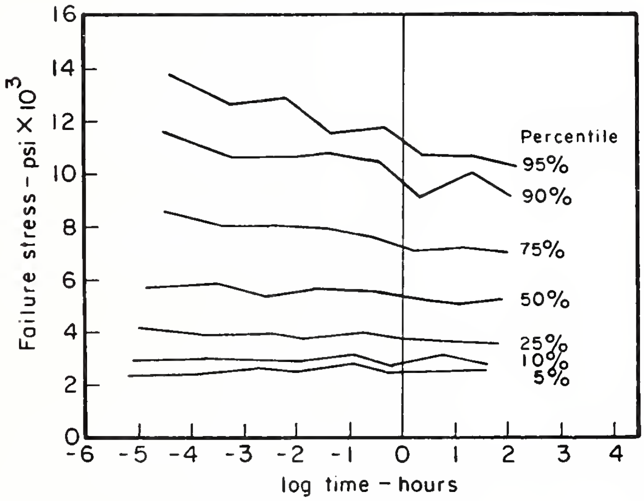


Figure 5.--Failure stress versus log time to failure. Rate of loading test.

This could well be explained by the presence of two different failure modes just as was the case for moisture content. The reason for stressing this point is that it does not appear to have been given prominent consideration in the present plans for future duration of load experiments. The investigation also indicates that the presently used duration of load factor of 2.0 for impact is inappropriate.

IN-GRADE TESTING

Before discussing some of the observations derived from In-Grade testing, it may be prudent to briefly review some of the background which led to the development of this testing philosophy.

The Limit States Design format introduced in Canada requires that "characteristic strength" values be used to describe the properties of the materials. These characteristic values have been chosen at the 5th percentile of the strength distribution. Testing with full size members during the early 1970s had clearly shown that it would be hopeless to use material values derived from small clear specimens for the purpose of Limit States Design.

It was, therefore, necessary to develop a testing system in which full size members were used to obtain 5th percentile values. However the variability of the present commercial grades would necessitate testing of large samples in order to obtain a reasonable level of confidence in the 5th percentile estimates. The load configuration had to be realistic and the cost of the testing could not be prohibitively expensive. The In-Grade testing method has the following features:

1) Full size members are used. Specimen preparation is minimal.

2) A proof load of a magnitude which will break 10-15% of the specimens is applied to all specimens of the sample. This cuts down the cost of material for testing purposes since unbroken material can be sold.

3) Rate of loading is such that the loading cycle takes about 30 seconds. This enables the testing crew to test about 300 specimens per day.

It was found that this testing philosophy can most economically be implementd by conducting the tests at the sawmill using specially designed portable equipment.

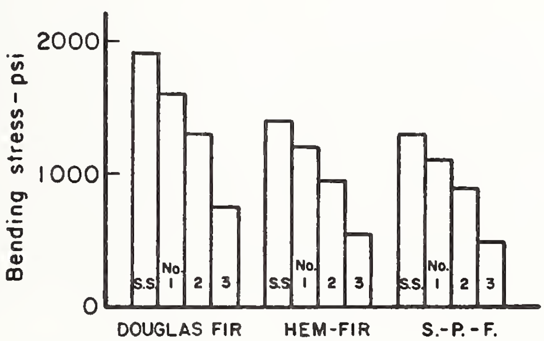
STRENGTH OF LUMBER GRADES

The In-Grade testing method was used in a testing program aimed at getting preliminary estimates of the "characteristic values" of the products produced in the sawmills using the present grading rules.

The present allowable bending stresses for joist and planks are shown in Figure 6 for the three species groups used in the tests. These allowable stresses are based upon tests with small clear specimens. The values for the Hem-Fir grades are 73% of the Douglas fir grades while the Spruce-Pine-Fir grades are 68% of the Douglas fir grades. The strength ratios for the different grades are:

S.S.	=	0.65
#1	=	0.55
#2	=	0.45
#3	=	0.26

The allowable stresses apply to all sizes since the grading requirements have been based upon, amongst other things, knot ratios.

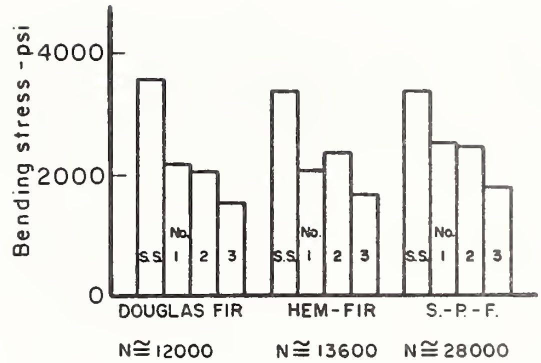


	DOUGLAS FIR	HEM-FIR	S.-P.-F.
SPECIES RATIOS:	1.0	0.79	0.68

GRADE RATIOS:			
S.S.	=	0.65	1.0
# 1	=	0.55	0.85
# 2	=	0.45	0.69
# 3	=	0.26	0.40

Figure 6.--Allowable stresses - bending.

The results from tests of the 2x8 output from many mills are shown in Figure 7. The lumber was correctly graded and the breaking value adjusted for moisture content effects. What is shown is characteristic values. It is evident that the species differences found in small clear specimens does not carry through to the commercial product. It is also evident that the concept of "knot ratio" is not valid since #1 grade and #2 grade have essentially the same strength.



	S.S.	#1	#2	#3
DOUGLAS FIR	1.00	0.60	0.57	0.43
HEM-FIR	1.00	0.61	0.70	0.49
S.-P.-F.	1.00	0.74	0.73	0.53
ASTM	1.00	0.85	0.69	0.40

Figure 7.--Characteristic values.

SIZE EFFECTS

The size effect (height) was also studied for two inch lumber in the mentioned tests. A very distinct height effect was found. Thus it was found that 2x4s were about 32% stronger than 2x10s for the same grade. This is contrary to our present concept which allows the same stresses for a grade regardless of size (height).

The strength of sawn timber was investigated in another test. About 700 specimens in the size range from 6x8s to 8x16s were tested. The combined results from the two tests are shown in Figure 8 for Douglas fir, #1 grade. The strength decreases with increasing height of the beam while the strength appears to increase with increasing breadth of beam (thickness). What is observed here is the combined effect of grading and the volume effect as predicted by the "weakest link principle". The size effects may well be different if another set of grading criteria were applied.

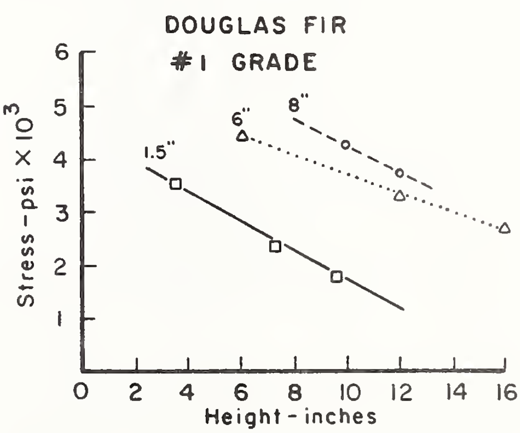


Figure 8.--Size effects.

A size effect was also observed in tension tests. The magnitude was similar to the one obtained in the bending tests.

GRADING

Further comments on our grading system is appropriate. The knot ratio concept is the cornerstone of our present visual grading system as far as strength is concerned. ASTM 245 details this system in five tables with more than 4,000 entries given to two significant digits. This infers an accuracy which at the best can be described as deceptive.

The defect which caused a board to fail in the In-Grade testing program was classified and measured according to the present grading rule. This information was then used to construct frequency curves for each kind of defect. Figure 9 shows such curves for wide face edge knots of different sizes for the 2x8 material. With a bit of good will, one can observe some slight correlation between strength and knot size on the average, but at the same time one should observe that the spread in the data is large and that a 7 mm knot can cause failure at the same stress as a 57 mm knot. One problem with our present grading system is that only knot size is considered and that the local slope of grain around the knot is neglected. Other researchers [6] [7] have also reported a very serious lack of agreement between strength and knot ratio.

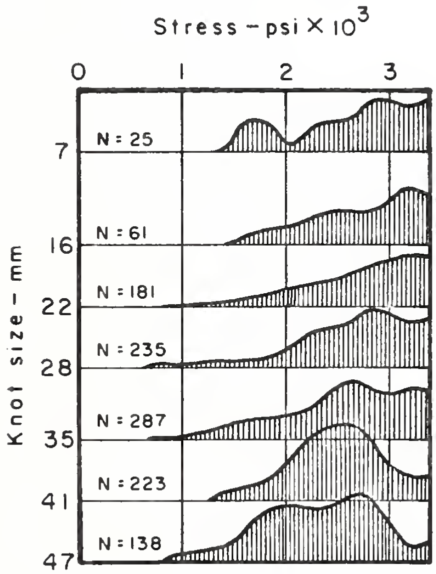


Figure 9.--Influence of knot ratio.

The coefficient of variation for the present grades is very high; 35-50%. This is a serious drawback for efficient structural use of the material. New grading rules should be developed based upon a rational testing program. Obviously, structural considerations should be first, but cosmetic defects should also be considered based upon the real needs of the user. Many requirements included in today's grading rules have no rational basis and are merely there traditionally.

One might think that mechanical grading could be the answer to this very central problem. It is, however, the authors experience that mechanical grading systems built upon a relationship between strength and stiffness will not be the proper answer. This relationship is a very weak one even when the measurements are made in the laboratory. Today's mechanical grades might be marginally better than our visual grades, but what is needed is a much more substantial improvement [8] [9].

It is possible that it will not be sufficient to use a single non-destructive parameter for predicting strength. Instead we might have to use a combination of several such parameters.

COMPRESSION PERPENDICULAR TO GRAIN

Thousands of tests have been carried out using the ASTM method for compression perpendicular to grain stresses. However, this test method, in which one-third of the top surface of a 2"x2"x6" clear specimen is loaded, is irrelevant for most structural applications. The load is carried in part by compression perpendicular to grain stresses and in part by shear forces along the edge of the loaded plate. Thus the test results do not represent a single material property and are, in addition, very dependent upon geometry.

Further work in this field may be worthwhile even though compression perpendicular to grain is only a problem in relatively few design cases.

COLUMN DESIGN

This topic is of importance in structural design but little reliable information is available in North America. Our present design procedures do not account for either internal or external eccentricities in a rational fashion. Very preliminary work with pure compression showed a size effect - smaller strength with increased volume. An increase in the allowable stress was, however, indicated. A verified method to deal with interaction of bending and compression stresses is also badly needed.

OTHER PROBELM AREAS

Design of joints is another important topic area which is in need of much research. We do not have a common base on which to evaluate the many types of structural joints. Yet connecting structural members is the most challenging design area for the practicing timber engineer. Long term behaviour is of real importance not only from the point of view of strength but also from the point of view of deformations. Creep could result in substantial redistribution taking place in statistically indeterminate systems.

Structural systems should be considered an area by itself in which much research is needed by competent structural engineers. However, before we can predict the behaviour of structural systems, we must know how the individual members or joints behave.

SHEAR

The lack of relevant research back-up in many areas central to Timber Engineering has been demonstrated above. However, not everything is lacking. As an illustration of excellent work carried out recently by the team of Foschi and Barrett regarding shear should be mentioned. They used the weakest link principle and fracture mechanics to tie together the experience with different types of shear specimens. Previously it was difficult to understand how tests with the ASTM shear blocks breaking at 1,400 psi could be related to large glulam beams failing at 400 psi. Their work is now included in the glulam section of the Canadian design code CSA-086.

Unfortunately, the code has not as yet adopted their theory to the lumber section. The Barrett and Foschi theory predicts that lumber (without splits) could have substantial increases in the allowable shear stresses. Such an increase could be very important for formwork design where shear often is the governing design criteria.

TYPE OF ANSWERS NEEDED

The solution to the problem areas mentioned above can be approached in several ways. A scientist who researches only for the sake of knowledge will seldom be satisfied with anything less than an answer which is "99% of the truth" (figuratively speaking). His approach will, of course, reflect his objective of great accuracy. An engineer, on the other hand, who has to use the information in conjunction with imperfect behaviour models and imperfect load information, will generally be satisfied with "95% solution". His approach to solving the problem may well be quite different. Obviously the cost and effort needed to obtain "99% solution" will in most cases exceed that which is needed for the "95% solution". It is important to keep this clearly in mind when contemplating the research needed to obtain solutions to the problem areas mentioned. If the research is to be directed towards the structural use of timber, we are looking for "95% solutions".

CRITIERIA FOR PRIORITIES

Before priorities can be firmly established, a more concise problem definition should be developed for each of the indicated topics. This should ideally be followed by a cost-benefit analysis. The above exercises should be done separately for single member applications and for structural systems. It is likely that some of the topics will have a different emphasis or definition depending upon which application is being considered.

Such a formal approach will not be presented here. Instead, the topics will be evaluated relative to the following questions:

A) *What is the magnitude of the discrepancy between preliminary test results and our present design practice?*

   We can, in some cases, estimate the discrepancy. Where this cannot be done, it may be advisable to conduct some preliminary experiments to get a feel for the problem.

B) *Is the indicated error on the unsafe side?*

   If that is the case, we may place the topic in a higher category of priority.

C) *How widely will the indicated change be applied?*

   Some topics will have a very narrow application, while others may affect a large number of designs.

There are, of course, other considerations such as: What is the cost of the research? When can the results be ready? Are interested researchers available? etc. All of these may influence the final priorities. They are, however, neglected in the following.

The relationship between each of the questions above and the research topics mentioned earlier will be presented below.

QUESTION A (Indicated Discrepancy)

1) Species Effect:

For the species groups investigated it would appear that the species differences in our design system (based upon small clear specimens) cannot be confirmed by In-Grade testing. Single member bending values for Hem-Fir and Spruce-Pine-Fir are underrated relative to Douglas fir.

Similar discrepancies were also found for single member tension values. The magnitude of the discrepancy in our present system is in the order of 50%.

2) Grade Effect (Knot Ratio):

Separating the grade effect from the species effect, one finds on the average for the three species groups that #1 grade over-rates the material by 25% while Select Structural, #2 grade and #3 grade under-rate the material by 4%, 1% and 21%, respectively. Similar results were also found for tension. However, #3 grade was not included in that testing program.

3) Height Effect:

It was found that the difference in strength on the 5th percentiles between 2x10s and 2x4s was in the order of 30%. The same trend is also indicated for the timber sizes. Again similar results were obtained for tension of lumber.

4) Thickness Effect:

The thickness effect appears to be substantial. An increase of 0-40% is indicated depending upon which height is considered.

5) Duration of Load:

Ball park figures for the change in the duration of load factor have been obtained from Figure 4.

1 hour	≅	10%
10 hours	≅	15%
100 hours	≅	20%
1000 hours	≅	20%
10000 hours	≅	10%

The estimates are reasonable for times up to about 2000 hours but beyond that the numbers will have a greater uncertainty. However, by far the most design cases involve loads which will last less than a total of 1500 hours during the life time of the structure. The indications are that the duration of load factor for impact loads will have to be reduced by about 20%.

6) Moisture Content:

A difference of 16% is presently being used between wet and dry service conditions for bending. It is unlikely that the small increases in strength indicated for wet material will find their way into about 15%.

7) Compression Perpendicular to Grain:

Indications are that changes in the allowable stresses would amount to about 10-15%. However, this would depend on what design criteria is chosen by the designer.

8) Design of Compression Members:

This topic is very wide since it apart from material properties also includes buckling phenomena as well as combined stresses. The author is not aware of estimates of the magnitude of the discrepancy, if any. Some preliminary testing to spot check our present methods seem indicated.

9) Structural Joints:

This topic is also very wide and requires a much more detailed analysis than can be presented here. However, it is likely that fairly large changes from our present methods can be expected particularly for cases where several connectors are employed simultaneously.

10) Structural Systems:

This field cannot be compared directly with our present design code. However, efforts will be required to make computer programs available to designers or for developing standard designs.

11) Strength Predictors:

The need for developing a rational and effective structural strength prediction systems permeates through most of the previous topics. Such a development could have great ramifications for the use of timber products as a structural material. The present system results in grades in which more than 60% of the pieces have a strength twice as strong as is needed (i.e. four times the allowable stresses).

QUESTION B (Safety)

Of the research topics mentioned, only two would appear to have discrepancies on the unsafe side. They are; species effect for Douglas fir and duration of load for impact.

QUESTION C (Field of Application)

1) Species effect
2) Grade effect
3) Height effect
5) Duration of load
11) Strength predictors

All the above topics would be applicable to all uses of structural lumber and timbers. They are therefore of special importance and will be given a rating of 100%.

4) Thickness Effect

This topic would have its application mostly to the category "Beams and Stringers". The volume produced is relatively small compared to the total industry output. Guesstimate; 10%.

6) Moisture Content

Relatively few structures are built in which wet service conditions prevail. Guesstimate; less than 5%.

7) Compression Perpendicular to Grain

This property is of some importance in engineered buildings since it influences the design and cost of steel connections. Design of concrete formwork could also be affected. Guesstimate; 5%.

8) Design of Compression Members

Better information on this topic would be applied to columns, chord members, walls, etc. This constitutes a fairly large number of applications. Guesstimate; 25%.

9) Structural Joints

This topic would apply to all structural applications of timber and lumber if one considered nails as a type of joint. Guesstimate; 100%.

10) Structural Systems

Structural design does involve systems and as such one could claim wide application for this topic. But even in the narrow sense of "load sharing" the topic would have wide applications. Guesstimate; 60%.

LIST OF PRIORITIES

The four following classifications of priorities are used: highest, high, medium and low. The order given within each classification is of course less pronounced.

	QUESTION		
	A	B	C
Highest Priority:			
Strength Predictors	50%+	No	100%
High Priority:			
Species Effect	30%	Yes	100%
Height Effect	30%	No?	100%
Grade Effect	20%	Yes	100%
Duration of Load	15%	Yes	100%
Structural Joints	?	No	100%
Medium Priority:			
Structural systems	?	No	60%
Design of compression mem	?	No	25%
Thickness effect	40%	No	10%
Low Priority:			
Moisture effects	15%	No	5%
Compression perp. to grain	10%	No	5%

The list above has been developed from the point of view of Timber Engineering as it is or should be reflected in our design codes. It is afirst attempt in which factual or preliminary information has been used wherever possible. Where such information was not available, guesstimates were used. These ought to be refined and the list expanded to include topics which might have been missed.

The listed topics represent a tremendous challenge to any researcher working in the Timber Engineering field. Ingenuity and innovative approaches will have to be employed to the fullest in order to solve the many central problems within a foreseeable future.

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MODELING RESPONSE UNDER AGGRESSIVE ENVIRONMENTS AND ACCELERATED TESTING[1]

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ABSTRACT

Modeling the response of wood-based materials in aggressive environments using kinetics is encouraged. Especial care must be exercised in accelerated tests to assure that the material undergoes the same reactions in the test environment as that expected in the environment being modeled.

INTRODUCTION

The luxury of conducting long-term experiments in which wood-base materials are subjected to a full range of degradative environment severities is normally impossible. Generally, the lower the severity, the longer the experiment is required to be conducted to detect significant changes. Long-term experiments (mos. and yrs.) are fraught with likelihood of experimental error as well. As a result, we attempt to model material response and conduct accelerated experiments to characterize the response over the severest conditions and extrapolate the response to less severe cases. A classic example is predicting residual strength of wood maintained at nearly ambient conditions by elevated temperature experiments.

Wood-base research literature is loaded with information on the end-effect of various environments on mechanical properties. It is abundantly clear that wood-base materials not only undergo immediate changes with exposure to various load and service environments, their strength characteristics additionally are continuously altered with duration of exposure. Unfortunately, this subjection to constant, cyclic, or random loads, heat, moisture, and chemical vapors normally degrades strength properties.

The changes are largely due to an alteration of structure or chemical constituents. Heat can induce pyrolysis and subsequent loss of hemicellulosic and cellulosic fractions. The presence of both moisture and heat accelerates hydrolysis. Acids and bases hydrolyze cellulose and hemicelluloses at room temperature. Some fungi and bacteria colonies grow in an accommodating environment within woods and consume wood constituents vital to structural integrity.

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KINETIC MODELS

A commonality among all the above environments and their influence is that they are kinetically describable. That is, they are amenable to description through the use of reaction rate theory of physical chemistry.

The rate of thermal degradation is tied to temperature of the material, for example, by an equation of the form:

$$\frac{dw}{dt} = -wA \exp[-\Delta E/RT] \qquad (1)$$

The equation predicts the weight loss rate, dw/dt, as a function of current weight, w, and absolute temperature, T. The factors A and ΔE are material constants dependent upon heating levels, and R is a constant. Stamm (1964) has given levels for A and ΔE for various wood-base materials.

When heating wood in a moist environment (such as steaming), a marked increase in weight loss occurs at the same heating level. This is manifested in the above equation by a marked reduction in the activation energy, ΔE, and reflects the additional effect of hydrolysis.

The rates of hydrolysis of wood-base materials due to action of acids and bases are governed by an equation of the above form as well. However, concentration, C, of the acid or base is important, and the rate increases with increasing temperature:

$$dw/dt = -w[kC^{m}] \exp[-\Delta E/RT] \qquad (2)$$

The growth of biological organisms also follows a similar model equation:

$$dP/dt - PA \exp[-\Delta H/RT] \qquad (3)$$

Here, P is the population and ΔH an activation energy. Because biological growth occurs within narrowly defined temperature and moisture conditions (e.g. m.c. > 20 pct and $40 \leq T \leq 140°$ F), application of the model requires careful definition of the environment and the presence of an innoculating organism. Certain fungi consume woody material for growth or perforate structural cells. As a result, population growth can be expected to influence loss of mass in direct proportion to population achieved.

To apply accelerated testing, then, to predict longer-term response one must be assured that the parameters in the kinetic equation are not changed or must be duly considered in analysis. To date, the research in accelerated testing has not evidenced this approach.

Let us, in particular, examine some aspects of predicting long-term strength using the results of tests conducted using elevated temperature as the accelerating medium. Table 1 indicates changes that occur in dry wood with an increase in temperature as derived from many researchers. Note that natural lignin structure is altered and hemicelluloses begin to soften at about 55° C (131° F). Hemicellulose content begins to decrease with an evident conversion to cellulose at about 120° C (248° F). About 100° C would appear to be an upper limit to use kinetic parameters applicable at 25° C. Most reported accelerated aging studies begin at a temperature of about 100° C and increase, Stamm (1964) and Millett and Gerhards (1972). As a result, extrapolations of the analysis to lower temperatures must be considered speculative.

Table 1.--Thermally induced changes in dry wood in an inert atmosphere

Temperature, deg C	
50	
55	Natural lignin structure is altered. Hemicelluloses begin to soften.
70	Transverse shrinkage of wood begins.
100	
110	Lignin slowly begins weight loss.
120	Hemicellulose content begins to decrease, α-cellulose begins to increase. Lignins begin to soften.
140	Bound water is freed.
150	
160	Lignin is melted and begins to reharden.
180	Hemicelluloses begin rapid weight loss after losing 4 percent. Lignin in torus flows.
200	Wood begins to lose weight rapidly. Phenolic resin begins to form. Cellulose dehydrates above this temperature.
210	Lignin hardens, resembles coke. Cellulose softens and depolymerizes. Endothermic reaction changes to exothermic.
225	Cellulose crystallinity decreases and recovers.
250	
280	Lignin has reached 10 percent weight loss. Cellulose begins to lose weight.
288	Assumed wood charring temperature.
300	Hardboard softens irrecoverably.
320	Hemicelluloses have completed degradation.
350	
370	Cellulose has lost 83 percent of initial weight.
400	Wood is completely carbonized.

RESEARCH NEEDS

The reaction rate kinetic model approach to predict durability of wood under various environments is both attractive and physically-chemically consistent to apply.

The development of kinetic theory for temperature and stress effects on mechanical properties is relatively well-delineated. Considerable effort is underway to test the success of the models to predict performance. Needed, however, is expansion to include the moisture content interaction and definition of the kinetic parameters below 100° C so that response at lower temperatures may be accurately dealt with.

Both chemical and fungal attack models require significant delineation and expansion to be applied to predict response. Particularly needed are prescription of limits of

applicability for active chemical and fungal attack.

The models should apply to predicting response of wood of small section or that is in intrinsic equilibrium with the environment. That is, no (or very little) diffusion of heat, moisture, or chemical is taking place. This is termed "homogeneous" reaction. In the real world, wood members or sections are often in a dynamic state and the reactions within the member become "diffusion-controlled." Dealing with the "homogeneous" state will be infinitely less complex than the "diffusion-controlled" cases as the latter will likely require finite element time-stepped procedures to analyze overall response.

Emphasized in these examples has been the prediction of weight loss of wood-base materials because weight loss has been highly correlated with the change in strength, Stamm (1964), Seborg (1953), Millett (1972), and Rusche (1975). A 5 percent loss in weight is found to indicate a 30 percent reduction in modulus of rupture, for example Millett (1972), and 15 percent losses in weight reduced tension and compressive strength more than 60 percent, Rusche (1975).

Other research has indicated that the immediate and long-term effects of load are similarly kinetically based, Schaffer (1973) and Gerhards (1977).

Duration of load and rate of loading effects on wood strength also have a kinetic model base. It has been shown that a model of the form:

$$\frac{df}{dt} = -f \{A \exp[- \frac{\Delta E}{RT} + \frac{B\sigma}{f}]\} \qquad (4)$$

results in being able to tie creep rupture to rate of loading failure times, Schaffer (1973). In this equation, f is the fraction of unbroken bonds in an element subject to stress, σ, and absolute temperature, T. It is of interest to note that a reduction of the equation to predict time to failure under either ramp loading or constant loading results in the familiar equation of form:

$$\sigma_f = A - B\ell n t_f \qquad (5)$$

Where t_f is the time to failure. It also reflects "damage accumulation," Gerhards (1977). Creep deformation is also accelerated by temperature, Schaffer (1977), and moisture, Bach (1965).

ACCELERATED TESTING

Reaction rate equations to predict immediate and long-term strength and deformation response in many environs are a consistent way to deal with the effects of deteriorating environments. However, to employ reaction rate kinetic models to interpret the results obtained in accelerated testing must be done with extreme care.

The basic approach in accelerated testing is to speed reactions that are normally slow at ambient conditions and extrapolate the results obtained in the "accelerated" environment to predict that at ambient. It is seen, for example, that elevating the temperature in thermal degrade experiments should allow one to reduce the time to reach a given weight loss according to equation (1). If done properly, this leads to the very useful application of the temperature - time superposition principle. Other time superposition techniques are possible as well (e.g. temperature-moisture content-time, temperature-chemical concentration-time, etc.).

One of the key requirements in using a kinetic equation is that the parameters used (A, ΔE, ...) apply strictly to the phase the material is in. That is, projecting the response of a material in one phase state to predict response in a second phase is not acceptable because the parameters change. This occurs in one case, for example, at about 325° C in pyrolysis of wood experiments (see fig. 1), Tang (1967). The change in slope indicates a change in ΔE has occurred and the reactions have been altered.

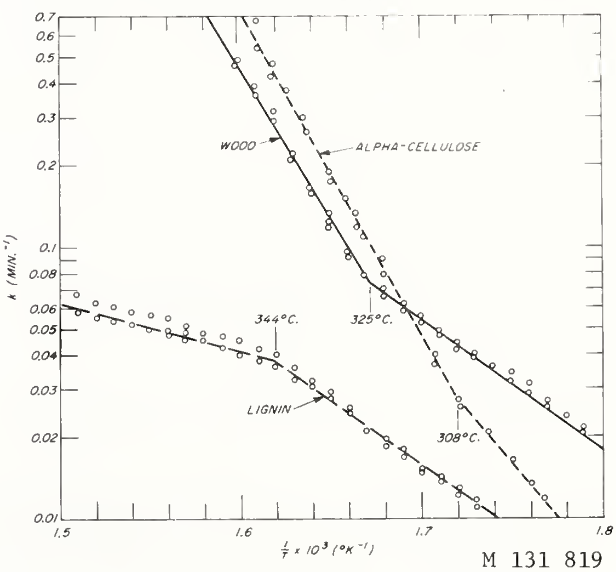

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Figure 1.--Arrhenius plot for pseudo first-order kinetics of pyrolysis of wood, alpha-cellulose, and lignin with no treatment from data of dynamic thermogravimetric analyses and rate of weight loss.

Dealing with cyclic temperature, moisture, stress, or chemical variation should not prove formidable after development and verification of proper kinetic models and quantification of parameters.

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